Optimized location of biomass bales stack for efficient logistics

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Abstract

1 Producers often aggregate bales into stacks before transporting these bales to an outlet
2 for consumption or delivery to industrial applications. Efficiency improvement in this
3 infield bale logistics will be beneficial. To address this an R simulation program involving
4 five methods for field stack location, namely field middle, middle data range, centroid,
5 geometric median, and medoid, as well as origin a direct aggregation method to outlet,
6 were developed. These methods were evaluated against field areas, ranging from
7 0.5–520 ha, for infield bale logistics (aggregation, transport, and total) using Euclidean
8 distances. The simulation used several input field variables, laid out bales based on yield
9 variation, determined optimized bale stack locations of methods, and evaluated distances of
10 aggregation to the stack, transport from the stack to the outlet, and total logistics. The
11 origin method used 1-bale handling tractor for direct aggregation to the outlet, while others
12 formed the bale stacks and transported bales to the outlet using 6-bales/trip equipment.
13 Results indicated for aggregation that geometric median was the best, followed by field
14 middle or centroid, middle data range, medoid, and finally origin. Methods aggregation
15 were about 76% and transport about 24% of the total (for >2 ha); and total distance were
16 about 65% of the origin. ANOVA, excluding origin, indicated that all methods were not
17 significantly different ($p < .05$) for the areas studied. The ‘field middle’ was recommended
18 as an easy and practical method for locating field stacks. Fitted power models described
19 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 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

50 distances. Thus, it was hypothesized that the bale stack location methods will be
51 significantly different from one another, from the viewpoint of infield logistics distances.

52 Several biomass logistics based studies addressing the biomass logistics in general,
53 supply of biomass to the biorefinery, economics of biomass logistics, and patents related to
54 bale forming and handling machinery were available. Studies involving biomass bale
55 logistics include development of integrated biomass supply and logistics (IBSAL) model
56 and its implementation for feedstock supply chain [2, 3]; development of a MATLAB
57 training tool on the timing and handling and storing round bales with a self-loading wagon
58 [4]; biomass bales transport system based on cotton logistics as model and explored the
59 difference and application [5]; herbaceous biomass bales transportation cost optimization
60 [6]; large biomass modules logistics system to maximize legal highway loads and to
61 minimize feedstock cost based on IBSAL [7]; hybrid genetic algorithm solution for the
62 efficient bale collection routes with a 15- and 35-bales wagon [8]; and simulation of the
63 bales layout mimicking the baler operation, and evaluation of several infield biomass bales
64 aggregation strategies [9].

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

78 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.

[Fig. 1 about here.]

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

106 makes the movement of bales from the stack to the outlet more efficient during transport.
107 This was because the aggregation can handle only a few bales (≤ 3) using a bale loader
108 (tractor attached to bale grapple or spear) compared to wagons/trucks that can handle
109 multiple bales (≤ 32) during transport. In this study, it was assumed that 1 bale was handled
110 in aggregation (e.g., tractor with grapple) and 6 bales in transport (e.g., open trailer) to
111 represent the most basic equipment available in the field. It was also recognized that with
112 the latest equipment, it was possible to handle multiple bales during aggregation (e.g.,
113 advanced automatic bale picker) and increase the number of bales (≥ 6) during transport.
114 The lower left corner (origin) of the field was assumed to serve as the outlet. It was also
115 assumed that the distances involved in aggregation and transport were obtained through
116 linear distance connecting the bales and the stack location coordinates, and that between
117 the stack and the outlet, respectively.

118 2.3. *Process simulation and parameters considered*

119 The processes involved in determining the efficient location of bale stack from the bales
120 layout along with analysis and visualization in the developed program are presented in the
121 form of a flowchart (Fig. 1B). Several inputs can be varied to accommodate different
122 scenarios to be studied. Areas representing actual field areas in the form of fractional
123 parcels of a “section” of land (259 ha) were considered. Thus, for the purpose of primary
124 analysis, the areas in hectares used in the simulation were 0.41, 0.51, 1.01, 2.02, 4.05, 8.09,
125 16.19, 32.38, 64.75, 129.5, and 259 ha. Furthermore, several areas at finer intervals (2 ha)
126 from 0.5 to 520 ha were used in the statistical analysis. The other parameter considered in
127 the simulation study were: length by width ratio of 1.0; biomass yield per hectare of
128 5 Mg/ha; harvester swath of 6 m; bale mass of 600 kg; percentage variation of biomass
129 yield of 5%, 7%, and 10%; number of bales moved during aggregation/trip was 1; and
130 number of bales moved during transport/trip was 6; and the random seed arbitrarily chosen
131 and used for random number generation in R that was 2015. Three simulated replications
132 are derived from the biomass yield percentage variation (5%–10%).

133 2.4. Optimum bale stack location methodologies

134 Optimum location is the most favorable spot on the field for stacking the bales so that the
135 total aggregation distance is the least. Many bale grouping/clustering (aggregation)
136 methods based on mathematical techniques of grouping points that are distributed on a
137 two-dimensional plane were considered. These geometrical points used in the grouping
138 were replaced by the layout of bales (Sec. 2.1) and mathematical techniques were applied.
139 Various methods selected for this study were field midpoint, middle data range, centroid,
140 geometric median, and medoid (Fig. 2). The hypothesis to be tested was the aggregation or
141 total distances of the methods will be significantly different from one another, and an
142 optimized method will emerge. Direct aggregation of bales to the field outlet was also
143 considered as one of the methods called ‘origin.’ Details of these six methods are given
144 next.

145 2.4.1. Field midpoint

146 Field midpoint was the simplest method of all. This represented a constant physical
147 midpoint of the field that was based on field dimensions, and was not affected by the bales
148 layout (Fig. 2). It is easy to locate the midpoint of the field by simply dividing the length
149 and width dimensions by two. Midpoint of a square or rectangular field can also be found
150 out using the midpoints or point of intersection of diagonals. In the simulation, the length
151 and width of the field were calculated from its area and the aspect ratio (length/width). The
152 x-axis represents the width of the field and y-axis the length. Thus, the field midpoint x-
153 and y-coordinates were calculated as:

$$\begin{aligned} \text{Length (m)} &= \sqrt{10\,000 \times \text{Area (ha)} \times \text{Length/Width}} \\ \text{Width (m)} &= \text{Area/Length} \\ \text{Field midpoint} &= \left(\frac{\text{Width}}{2}, \frac{\text{Length}}{2} \right) \end{aligned} \quad (1)$$

158 2.4.2. Middle data range of bale coordinates

159 Middle data range of bale coordinates is the number that separated the data set’s upper half
160 from the lower (Fig. 2). From the bale coordinates (x_i, y_i) , which were stored as

one-dimensional vectors, the minimum and maximum values of each vector were obtained using the R's 'min()' and 'max()' standard functions. Therefore, the middle value of the bale coordinates was obtained as:

$$\text{Middle data range} = \left(\frac{\min(x_i) + \max(x_i)}{2}, \frac{\min(y_i) + \max(y_i)}{2} \right) \quad (2)$$

where x_i and y_i are the x - and y -coordinate vectors of the bales layout, respectively.

2.4.3. Centroid of bale coordinates

Centroid of an area is similar to the center of mass, center of gravity of a body, **or barycenter, which is** the point at which the whole body can be balanced. Centroid of a plane is also known as its 'geometric center.' **Similar to the mean, the location of the centroid minimizes the weighted sum of generalized squared Euclidean distances from vector to any points in the space [12].** Applying this concept to a set of points in a plane, the centroid represents the mean position of all the points both in x and y directions (Fig. 2). The centroid was determined using R's 'mean()' standard function, and was expressed with usual notations as:

$$\text{Centroid} = \left(\frac{1}{n} \sum_{i=1}^n x_i, \frac{1}{n} \sum_{i=1}^n y_i \right) \quad (3)$$

where n is the total number of bales in the field.

2.4.4. Geometric median of bale coordinates

Geometric median is similar to median, however it is used to compute median for multivariate data and multidimensional spaces. Geometric median of points generated randomly in the X - Y plane is the point from which the sum of Euclidean distances of all the randomly generated points is the least (Fig. 2). Thus, by definition, the geometric median will be the best location for the bale stack. However, it will be useful to statistically compare this method with other simpler methods. There were no explicit formulae for geometric median determination, **but iterative process could be used.** Theoretically, for a given set of m points $x_1, x_2, \dots, x_m$ with each $x_i \in \mathbb{R}^n$, the geometric median was defined as:

$$\text{Geometric median} = \arg \min_{y \in \mathbb{R}^n} \sum_{i=1}^m \|x_i - y\|_2 \quad (4)$$

The ‘arg min’ of Eq.(4) means the value of the argument y which minimizes the sum. In this case, it was the point y from where the sum of all Euclidean distances to the x_i ’s was minimum. Using the R package ‘pracma,’ the geometric median of random points in the two-dimensional space was calculated. This package solved the task by applying an iterative process known as the Weisfield’s algorithm [13]. This algorithm defined a set of weights that were inversely proportional to the distances from the current estimate of the samples; and created a new estimate that was the weighted average of the samples according to these weights.

2.4.5. Medoid of bale coordinates

Medoid is defined as a representative object of a data set or a cluster with a data set whose average dissimilarity to all the objects in the cluster is minimal. It was more robust because it minimized the sum of dissimilarities instead of the sum of squared Euclidean distances. The medoid is similar to mean or centroid, but it always belongs to a member of a data set (Fig.2), unlike the other methods studied. Cluster analysis is required to find the medoid of the X-Y plane. Clustering is the process of grouping data objects into a set of disjoint classes, called clusters. The objects within a class have high similarity to each other while objects in separate classes are more dissimilar [14].

The medoid was calculated using the algorithm called partitioning around medoids (PAM) with the R package ‘cluster’ [15, 16]. For bale aggregation, the medoid was evaluated by setting the number of clusters equal to one. The evaluated medoid coordinates coincide with one of the bale coordinates while in the other methods it may be a point in the field. This means it was easy to mark the medoid on the field, which was nothing but identifying a particular bale (Fig.2).

2.4.6. Field origin

Origin is the basic and the most simple method where all bales are directly aggregated to the final outlet. It is also the method where no bale stacks are involved in the bale

214 collection. In this method, only bale loader was used in aggregation and bales were directly
 215 collected to the outlet; hence, will not have the transport component and the aggregation
 216 and total logistics were the same. As the loaders were used in the direct collection of the
 217 origin method, and with one bale handling assumption, the logistics distances tend to be
 218 the greatest. The origin method can serve as the ‘reference method’ to compare the other
 219 methods.

220 2.5. Aggregation to stack location or to outlet

221 The aggregation distance determination involved the sum of Euclidean distances of all the
 222 bales (x_i, y_i) to the point of interest (e.g., methods bale stack location, origin). The point of
 223 interest with methods were the different bale stack locations coordinates (x_m, y_m) , and for
 224 the origin method this was the origin $(0, 0)$. Therefore, the aggregation distances of the
 225 methods and that of origin are:

$$226 \quad \text{Aggregation to stack} = \sum_{i=1}^n \sqrt{(x_i - x_m)^2 + (y_i - y_m)^2} \quad (5)$$

$$227 \quad \text{Aggregation to origin} = \sum_{i=1}^n \sqrt{(x_i - 0)^2 + (y_i - 0)^2} \quad (6)$$

229 Only the direct single distance connecting the bales location to the point of interest as
 230 described through Eqs.(5)-(6) was considered in the analysis. However, for practical
 231 operation that involved to-and-fro movement of the equipment, this distance should be
 232 doubled.

233 2.6. Bale transport to the outlet

234 The stacked bales at the optimum locations, based on different methods other than origin,
 235 have to be transported to the outlet. The lower-left corner of the field was considered as the
 236 outlet in this study, and it coincided with the origin of the field. It was assumed that
 237 6-bales/trip were transported using a bale wagon/truck from the stack location. The total
 238 transport distance can be obtained from the constant distance between the bale stack
 239 location and the origin times the whole number of 6 bales-trips ($N_{6,\text{bales}}$) to include all the
 240 bales of the stack. The transport distances determined were similar to the aggregation

process (Eqs. (5)-(6)) but they involved simply the bale stack location of the five methods and the outlet (0, 0) as:

$$\text{Transport to outlet} = N_{6_bales} \times \sqrt{(x_m - 0)^2 + (y_m - 0)^2} \quad (7)$$

The collection equipment for transporting round bales includes bale loaders (tractor with grapple; also used in aggregation), and bale wagons/trucks. The different types of bale loaders can handle 1, 2, or 3 bales. Based on the design and capacity, the bale wagons can transport 6, 12, 26, 30, 32 or more bales. There are also other advanced automatic bales pickers that combine the operations of bales loader and wagon, and capacities of 6, 10, and 14 bales [9]. These bale pickers can also be used for aggregation, but their application was not considered in the study.

2.7. Comparison of bale stack location methods

The distribution of the bale stack locations from the different methods in the X-Y plane, as it varies with different field areas, is a measure of the variations produced by these methods. One way of evaluating the distribution is by measuring the closed polygonal distance of the stack locations for the five methods. This distance can be evaluated by simply connecting the distances in the order of the methods and termed ‘methods distance’ (MD) or finding the least distance of a unique polygonal path following the ‘traveling salesperson’ (TSP) technique [17].

The MD was calculated by adding the distance among various stack locations in the order of the methods used in the analysis, which was arbitrary. The TSP distance was calculated by using the R package ‘TSP’ [18]. This package deals with Euclidean TSP problem of traversing each point once with the least possible route and solves the problem from the set of points. It is expected that the TSP distance will be smaller than the MD. When the bales locations from different methods converge, as affected by the area of the field, the MD and TSP values will reduce and signify that the methods are not different from one another and *vice versa*. Therefore, MD and TSP distances serve as measures to quantify the variation of bale stack locations generated by different methods and compare them.

2.8. Statistical analysis

Apart from simulation model development (Fig. 1B), R [11] was also used for statistical analysis and results visualization. The one-way ANOVA was carried out to test the significant difference between the means of two or more aggregation methods studied. In the ANOVA, the ‘origin’ method was not considered as it was different and no bale stack was produced in the field before transport to the outlet. Aggregation and total logistics (aggregation + transport) were considered as dependent variables. Statistical significance at α of 0.05 and 0.001 was considered. Based on the results, a practical method will be selected and further analysis, such as correlation and regression model development using R’s ‘cor()’ and ‘lm()’ commands, respectively. Pearson correlation between area and the logistics distances were evaluated to understand the association of these variables. Suitable regression models were developed with logistics distances as the dependent and field area as the independent variables. The model style was selected by observing the plot diagnostics (e.g., residuals). For visualization and presentation of graphical results, R packages like ‘base’ and ‘ggplot2’ were used.

2.9. Field shape effect on bale logistics

The bale stack location methods described thus far considered only square and rectangular field shapes (Fig. 3). In U.S. land surveying it is common to delineate parcels of farmlands in terms of square “sections” (259 ha) to enable mechanized agriculture. Therefore, most of the field shapes are square or rectangular, as they were derived usually by divided from these standard sections of land. However, some of the fields tend to be of other shapes as well, such as circular (pivot-irrigated fields) and other polygonal shapes due to exiting boundaries of the land holdings in the U.S. and other parts of the world.

The cultivation practices (e.g., planting, spraying, harvesting) most of the times follow a concentric pattern based on the field shapes (e.g., circular/spiral in pivot-irrigated fields). In such cases the bale layout simulation for square and rectangular fields outlined earlier (Sec. 2.1) will not work and new specific simulation algorithms should be developed, and this may require a future study. However, once the coordinates of bales layout for different

298 shapes were obtained, the bale stack locations methods and other other analysis described
299 above (Fig. 1B) will be equally applicable.

300 **3. Results and discussion**

301 *3.1. Bale stack location methods distribution*

302 The hypothesis of different stack location from methods lead to significantly different
303 results can be visualized by plotting their locations among the bales layout. To illustrate
304 the various bale stack locations generated by the methods, a small field of 0.8 ha that made
305 only 5 (600 kg) bales was plotted to show the extent of the field (Fig. 2).

306 [Fig. 2 about here.]

307 [Fig. 3 about here.]

308 The field midpoint (blue cross) was a fixed location based on the field dimensions
309 while the other methods were based on the bales layout data. It can be seen that the
310 centroid, middle data, and geometric mean methods locations were on the field between
311 the bale locations (green circles), but the medoid coincided with the third bale (from left)
312 location (Fig. 2). Given the layout of these bales the geometric median (brown circle) was
313 the best location to aggregate the bales into a stack. However, the middle data (pink circle)
314 and centroid (blue circle) methods were not much separated from the geometric median.
315 The field outlet (gray diamond), which is the left bottom field corner, is the origin and to
316 where all the bales will be finally transported. It was possible to have the outlet anywhere
317 along the boundary of the field, but the origin was considered in this study, which was
318 equivalent to any other three corners of the field.

319 To visualize the bale stack locations and their distribution in the field, a 'section'
320 (259 ha) area was considered in the background and four field areas of 32.5, 65, 130, and
321 259 ha were overlaid (Fig. 3), unlike the zoomed-in view of an exclusive small field (Fig. 2).
322 This plot indicates that all the methods' stack locations converge and methods were
323 indistinguishable irrespective of the areas (32.5 through 259 ha) and the shape (square and
324 rectangular) tested. This cursory observation indicated that the alternative hypothesis,

325 which implied that all the methods were statistically similar, was true. However, through
326 rigorous statistical analysis, the correct variation will be revealed.

327 3.2. *Optimized bale stack location methods results*

328 Bale stack aggregation methods generated different locations with respect to several field
329 areas considered. These locations produced the associated logistics distances. The logistics
330 distances and the distribution of stack locations evaluated through MD and TSP were
331 determined and presented (Table 1). The origin method had the highest aggregation among
332 all methods and areas, whereas the other methods' aggregation distances were different and
333 they did not vary much from one another because of convergence of locations (Fig. 3). As
334 the origin method directly collected all the bales to the outlet during the aggregation, the
335 transport component was not present (Table 1). However, the origin method was not as
336 efficient as the other methods, because only single bale was handled each time that
337 increased the logistics distance.

338 [Table 1 about here.]

339 Among the other methods, the geometric median was the most efficient with the
340 lowest aggregation distance for all areas, and the reason being the very definition of this
341 method to produce the least grouping distance (Table 1). Similarly, the least efficient (areas
342 ≥ 2.02 ha) was the medoid with the largest aggregation distance. The reason being the
343 medoid was restrictive and made to coincide with an existing bale location, which might be
344 away from the optimum location in the field. Field middle method closely followed the
345 best geometric median method, while the middle data range and centroid methods also had
346 a similar trend with no clear best.

347 The transport component was always lower than the aggregation because multiple
348 bales (6-bales/trip) were transported from the bale stack to the outlet (Table 1). The trend of
349 total logistics distance (aggregation + transport) did not follow the similar trend of
350 aggregation, as the transport component was different for each method. For example, the
351 bale stack location closer to the outlet produced a smaller transport distance than stacks
352 away from the outlet. Thus, sometimes even though the geometric median produced the

lowest aggregation distance, the total distance was always not the best. In general, when the total distance was considered, all the methods had similar values but the origin was always significantly larger compared to the other methods.

3.3. *Effect of field area on the bale stack location methods*

Increased field area obviously produced more bales but in an overall sense, it did not affect the ranking of the methods. It was evident from the area results (Fig. 4): (i) all logistics distances increased with area; (ii) origin method's aggregation distances were significantly higher (about twice) than the other methods; (iii) for the rest of the methods, aggregation were similar; (iv) methods' aggregation other than origin were about 76% and transport about 24% of the total (for >2 ha); (v) the transport distances, however, were about 32% of aggregation or 24% of total; (vi) with the multiple 6-bales transports, the total distance of the methods were still significantly smaller (about 65%) than the origin; and (vii) no clear distinction was observed in the total distance among the methods other than the origin. Overall, since a similar pattern emerged for all logistics distances (Fig. 4), it can be concluded that field areas or the number of bales did not affect the ranking of the methods. This also indicated that any method other than the origin can be equally used.

[Fig. 4 about here.]

3.4. *Distribution of bale stack location methods*

The distribution of the methods (excluding origin) were studied through MD and TSP distances (Table 1). The TSP distances were always smaller than the MD. Both these values were quite small ($MD \leq 0.114$ km and $TSP \leq 0.1$ km) compared to the total distance (0.13–4927 km) for the area range studied (0.41–517 ha). These low values of the methods distribution (MD and TSP) indicated that there was no variation in the layout distribution among the methods, irrespective of the area or number of bales, as earlier observed (Fig. 3).

A plot of these distributions with a series of areas from 0.5 to 520 ha at 2 ha intervals helped further to explore any converging trend of these distributions (Fig. 5). Along with MD and TSP, the difference between the two allowed for easy comparison. The TSP was most often smaller than MD, but the difference was very small in most areas as well. The

381 pattern of these distribution parameters did not show any convergence with the increase in
382 area. These variations, however, changed with different random number seeds (e.g., 2016
383 and 2017; [Fig.5](#)). This result showed that there was no particular area where the methods
384 distances converge. The emergence of random variation or no trend again confirms the
385 non-convergence of the methods distribution. Thus, any method other than origin can serve
386 well and this observation is applicable to any area.

387 [Fig. 5 about here.]

388 3.5. *Statistical analysis results*

389 The analysis was conducted using the one-way ANOVA, where the methods (excluding
390 origin) were tested for their significant difference based on field areas (0.5 to 520 ha at 2 ha
391 intervals) and biomass yield variations (5%, 7%, and 10%) produced the replications. The
392 ANOVA results are given in the form of a figure showing the significant difference at
393 p -levels of 0.05 and 0.01 for aggregation and total logistics distances ([Fig.6A](#)).

394 [Fig. 6 about here.]

395 The results showed that several areas ($\leq 11.8\%$) produced significant differences
396 among the methods, while the predominant area ranges were not for aggregation and total
397 logistics ([Fig.6A](#)). Of the 262 levels of areas studied, 7 (2.7%) and 4 (1.5%) areas were
398 significantly different for aggregation and 31 (11.8%) and 12 (4.6%) for total logistics at
399 p -levels of 0.05 and 0.01, respectively. No single area cutoff was found that divided the
400 methods to be significant. The results were obtained by a random seed of 2015, and the
401 results patterns were expected to be different with other seed values as observed earlier
402 ([Fig.6A](#)).

403 3.6. *Comparison of geometric median and field middle methods*

404 A further analysis was performed to exclusively compare the best geometric median (GM)
405 and simplest field middle (FM) methods closely considering 262 areas continuously from
406 0.5 to 520 ha at an interval of 2 ha for windrow variations of 5%–10% ([Table2](#)). The actual

407 values of both methods were close showing only a deviation of $\geq \pm 0.2\%$ GM from FM for
408 areas ≤ 4 ha with aggregation and ≤ 34 ha with total logistics distances, and no deviations
409 with larger areas (data not shown). By principle, the GM should yield the lowest
410 aggregation distances. It was found that GM was exclusively lower than FM for $\leq 85.5\%$,
411 and coincides with FM for about 14%–21% of cases, which resulted in $\leq 99.6\%$ cases for
412 $GM \leq FM$.

413 [Table 2 about here.]

414 With the total logistics distances, GM was equally lower than FM in a reduced range
415 of 44%–58%, but will be greater than FM for 41%–56% (Table 2). Even though in
416 aggregation GM was the most efficient, in total distance either GM or FM were equally
417 good, because the transport distance that affects the total logistics will be greater if the GM
418 location was away from the outlet compared to FM. Thus, it appears that both GM and FM
419 were located towards the outlet equally leading to reduced total logistics distances.
420 Furthermore, the actual deviations between GM and FM ($\geq 0.2\%$) were very low, as the
421 number of cases was $\leq 1.5\%$ for aggregation and $\leq 3.8\%$ for total logistics distances. These
422 deviations were observed only in the lower ranges of field areas ≤ 4 ha and ≤ 34 ha for
423 aggregation and total logistics, respectively. In addition, a 1% deviation or more was
424 observed only with 1 ha field area or less for both distances. Based on these results and
425 considering the simplicity, the FM can be readily recommended as the method for bale
426 stack location, as the FM was easy to delineate and practical to use.

427 The differences in strategies between the recent [10] and the present studies lies in the
428 locating the field stacks, namely the former used directly the mid-edges along the
429 boundaries of the field, field corners, and field middle, but the latter used the bale layout
430 coordinates to arrive at several methods around the field middle to determine the optimum
431 location, but rest of the evaluation of bale logistics distances are the same. The previous
432 study [10] indicated that formation of stacks in the middle of the subfield compared to
433 mid-edges or corners significantly reduced the all logistics (aggregation, transport, and
434 total) distances. While the present work supporting the previous findings, it further
435 indicates that unless the subfield areas are ≤ 1 ha the FM is the best location for the bale

stacks. Based on the results, for smaller field areas (≤ 1 ha), GM is the best location for aggregation, and the total logistics should be decided according to the nearness of GM or FM with respect to the outlet.

3.7. Regression models of logistics distances

Even though the aggregation distances of the FM were larger, especially with smaller areas (≤ 1.01 ha) with fewer bales (≤ 8), the total distance was comparable to the other methods (Table 1). For areas ≥ 2.02 ha, the difference of the total logistics distance of FM ranged only from -0.34% to 0.18% with reference to the best method in each area. Exclusive comparison between GM and FM (Table 2) also supports this observation. Similar differences were expected in the other intermediate areas comparing other methods, but were not tested. Therefore, for practical use and simplicity, the FM method was selected for further correlation analysis and regression model development. The logistics distances (aggregation, transport, and total) with field areas incorporating the biomass yield variation (0.5 to 520 ha $\rightarrow$ 262 areas; 3 yield variations of 5%, 7%, and 10%; 786 data points) were well correlated and the Pearson's correlation coefficients are ≥ 0.989 .

The basic plot of area versus logistics distances showed a power variation. Therefore, the simplest linear model was found inadequate and the regression diagnostics of residuals revealed a systematic pattern (parabolic). However, with logarithmic transformation both for area and logistic distances, the linear variations were observed and power models were developed (Fig. 6B). The following models of logistics distances of the FM method had excellent fits ($R^2 > 0.99$):

$$\text{Aggregation (km)} = 0.325 \times \text{Area (ha)}^{1.497} \quad (R^2 > 0.99)$$

$$\text{Transport (km)} = 0.108 \times \text{Area (ha)}^{1.483} \quad (R^2 > 0.99)$$

$$\text{Total (km)} = 0.434 \times \text{Area (ha)}^{1.493} \quad (R^2 > 0.99)$$

Residuals of these models did not show any systematic variation and the models were acceptable. These models are easy to apply and estimate the logistics distances from the areas. Because the difference in the logistics distance of the other methods was coinciding,

464 a similar power model variations were expected as well with other methods.

465 The **bale stack location methods** can be extended to multiple bale stacks, wherein the
466 large field can be conceptually divided into smaller subfield units and the bales stacks were
467 made at each subfield **as reported earlier [10]**. Then the bales of the multiple stacks can be
468 transported as usual to the outlet. As the harvest usually takes place for the entire field in a
469 single stretch, the bale formation can be for the whole field, but the stacks formation can be
470 for the identified subfields. The outlets can also be located anywhere along the field
471 boundary (e.g., middle of width, middle of length) or even at the center or other locations
472 based on farmstead location, especially when existing roads/pathways were available. With
473 such alternate locations for the outlet, all the logistics distances will be different and
474 smaller, as the corner outlet was the farthest point from the field middle. Future research
475 work should address these multiple bale stacks, **locations of various outlets, other field**
476 **shapes, use of automatic bale-picker for aggregation,** the economics involved, **and their**
477 **effect on the various bale stack location methods** in the infield bale logistics operations.

478 **4. Conclusions**

479 Five bale stack location methods, namely field middle, middle data range, centroid,
480 geometric median, and medoid, as well as a direct bale aggregation method to the outlet
481 were simulated and compared using a developed R-program. The geometric median
482 followed by field middle, middle data range, medoid, and finally origin were the best
483 method for bale stack location. Methods' aggregation were about 76% and transport about
484 24% of the total (for >2 ha); and total distance were about 65 % of the 'origin.' Distribution
485 of the five bale stacking methods evaluated through 'grouped methods distance' and 'travel
486 salesperson' did not follow any pattern with field areas, which indicated no convergence
487 and meant any method can be applied equally. Even though ANOVA indicated that several
488 areas ($\leq 11.8\%$) produced significant differences among the methods ($p < 0.05$),
489 predominant area ranges (0.5–520 ha) were not different for aggregation and total logistics
490 excluding origin for the 6-bales/trip transport. **Only 1% deviation or more was observed**
491 **with field area ≤ 1 ha for both aggregation and total logistics distances, when geometric**

492 median and field middle methods were exclusively compared. Therefore, the ‘field middle’
493 was recommended as an easier and practical method because its location can be readily
494 obtained. All the logistics distances of field middle method with 6-bales/trip were well
495 described by power models ($R^2 > 0.99$). These logistics models can be used to predict the
496 aggregation, transport, and total distances from the field area of interest (0.5–520 ha).

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Table 1

Methods of optimum bale stack locations and their logistics distances and methods combined distances.

Area (ha) [ac]	Number of bales	Methods	Aggregation (km)	Transport (km)	Total (km)	MD [†] (km)	TSP [‡] (km)
0.41 [1]	3	Origin	0.196	0	0.196	0.070	0.045
		Field middle	0.085	0.045	0.130		
		Middle data range	0.070	0.061	0.131		
		Centroid	0.068	0.062	0.130		
		Geometric median	0.065	0.064	0.129		
		Medoid	0.068	0.075	0.143		
0.51 [1.25]	4	Origin	0.240	0	0.240	0.054	0.048
		Field middle	0.107	0.050	0.158		
		Middle data range	0.108	0.052	0.160		
		Centroid	0.102	0.057	0.159		
		Geometric median	0.099	0.067	0.166		
		Medoid	0.101	0.072	0.172		
1.01 [2.5]	8	Origin	0.462	0	0.462	0.095	0.051
		Field middle	0.404	0.142	0.546		
		Middle data range	0.205	0.109	0.315		
		Centroid	0.206	0.114	0.320		
		Geometric median	0.205	0.109	0.314		
		Medoid	0.206	0.103	0.308		
2.02 [5]	18	Origin	1.80	0	1.80	0.054	0.034
		Field middle	0.87	0.30	1.17		
		Middle data range	0.87	0.30	1.17		
		Centroid	0.86	0.31	1.17		
		Geometric median	0.86	0.31	1.18		
		Medoid	0.89	0.35	1.24		
4.05 [10]	33	Origin	5.26	0	5.26	0.144	0.100
		Field middle	3.11	0.85	3.96		
		Middle data range	3.11	0.86	3.97		
		Centroid	3.11	0.86	3.97		
		Geometric median	3.11	0.88	3.99		
		Medoid	3.45	1.09	4.53		
8.09 [20]	67	Origin	14.63	0	14.63	0.024	0.021
		Field middle	7.29	2.41	9.71		
		Middle data range	7.29	2.43	9.72		
		Centroid	7.29	2.43	9.72		
		Geometric median	7.28	2.45	9.73		
		Medoid	7.29	2.41	9.70		
16.19 [40]	133	Origin	40.67	0	40.67	0.074	0.072
		Field middle	20.28	6.54	26.82		
		Middle data range	20.29	6.61	26.89		
		Centroid	20.28	6.51	26.79		
		Geometric median	20.28	6.58	26.86		
		Medoid	20.52	6.88	27.39		
32.38 [80]	270	Origin	117.89	0	117.89	0.060	0.052
		Field middle	58.92	18.11	77.03		
		Middle data range	58.92	18.22	77.14		
		Centroid	58.92	18.16	77.08		
		Geometric median	58.92	18.19	77.11		
		Medoid	59.18	18.11	77.29		
64.75 [160]	540	Origin	333.12	0	333.12	0.049	0.043
		Field middle	166.52	51.21	217.73		
		Middle data range	166.53	51.41	217.93		
		Centroid	166.52	51.26	217.78		
		Geometric median	166.52	51.30	217.82		
		Medoid	166.81	51.23	218.05		
129.5 [320]	1082	Origin	943.38	0	943.38	0.051	0.029
		Field middle	470.83	145.65	616.48		
		Middle data range	470.83	145.79	616.62		
		Centroid	470.83	145.91	616.74		
		Geometric median	470.83	145.83	616.66		
		Medoid	471.26	148.53	619.79		
259 [640]	2163	Origin	2665.34	0	2665.34	0.028	0.027
		Field middle	1331.20	410.81	1742.01		
		Middle data range	1331.21	411.45	1742.66		
		Centroid	1331.19	411.07	1742.27		
		Geometric median	1331.19	411.25	1742.44		
		Medoid	1331.32	407.51	1738.83		
517 [1280]	4324	Origin	7531.35	0	7531.35	0.022	0.020
		Field middle	3765.75	1160.34	4926.09		
		Middle data range	3765.77	1160.95	4926.72		
		Centroid	3765.75	1160.51	4926.26		
		Geometric median	3765.75	1160.39	4926.15		
		Medoid	3765.86	1159.71	4925.57		

[†] MD - Methods distance i.e. total polygonal distance of all methods taken in the selected order; [‡] TSM - Traveling sales man distance i.e. total polygonal distance of all methods following traveling sales man technique; Origin was the outlet location where bales were finally transported; and medoid was the aggregation method where it coincided on one of the field stacks but other methods may not.

Table 2

Comparison of field middle and geometric median logistics among various field areas from 0.5 to 520 ha.

Windrow variation (%)	Aggregation (% cases)			Total logistics (% cases)		
	GM<FM	GM≤FM	Abs.GM:FM Dev. ≥0.2% [†]	GM<FM	GM>FM	Abs.GM:FM Dev. ≥0.2% [†]
5	78.2	99.2	1.5	44.3	55.7	3.4
7	81.7	99.6	1.1	46.6	53.4	3.8
10	85.5	99.2	0.8	58.4	41.2	3.8

[†] - Percent of cases having absolute deviation of GM with respect to FM ≥0.2%; GM - Geometric median; FM - Field middle. The total number of field areas considered continuously spaced at 2 ha = 262.

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Fig. 1. (A) Formed bales on the field ready to be aggregated into bale stacks, and (B) flow diagram of process simulation of bale stack aggregation methods, infield transport logistics, and statistical analysis.

Bale aggregation methods (bales = 5; area = 0.8 ha)

Fig. 2. Bale aggregation methods studied are illustrated with a small field area (0.8 ha) with a limited number of bales ($n = 5$).

Fig. 3. Bales layout and bale aggregation methods location for different field areas overlaid in a section area of land. Simulation data: biomass yield/ha = 5 Mg; bale mass = 600 kg; harvester swath = 6 m; aspect ratio = 1.0 and 0.5; random variation in biomass yield = 10%; and random number seed used = 2015.

Fig. 4. Aggregation, transport, and total logistics distances of different aggregation methods studied as presented in Fig.3. The number of bales hauled per transport trip was six.

Fig. 5. Variation of grouped methods except origin and traveling sales person distance, its difference, and the effect of random number generation seeds.

Fig. 6. (A) ANOVA of aggregation and total logistics as influenced by field area. Field parameters used were similar to Fig. 3. The presence of a bar represents a significant difference among studied methods but origin, at that field area and level of significance (p -value). The total refers to the sum of aggregation and transport with 6-bales/trip. (B) Fitted power models for logistics distances for the selected field middle method.

Graphical abstract