4-2014

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ARTICLE INFO

Article history:
Received 31 December 2011
Received in revised form
27 February 2014
Accepted 11 March 2014
Available online 27 April 2014

Keywords:
Baler
Bale layout
Collection
Farm machinery
Field stack

ABSTRACT

Biomass bales often need to be aggregated (collected into groups and transported) to a field-edge stack or a temporary storage before utilization. Several logistics scenarios for aggregation involving equipment and aggregation strategies were modeled and evaluated. Cumulative Euclidean distance criteria evaluated the various aggregation scenarios. Application of a single-bale loader that aggregated bales individually was considered as the "control" scenario with which others were compared. A computer simulation program developed determined bale coordinates in ideal and random layouts that evaluated aggregation scenarios. Simulation results exhibited a "diamond pattern" of bales on ideal layout and a "random pattern" emerged when ≥10% variation was introduced. Statistical analysis revealed that the effect of field shape, swath width, biomass yield, and randomness on bale layout did not affect aggregation logistics, while area and number of bales handled had significant effects. Number of bales handled in the direct method significantly influenced the efficiency. Self-loading bale picker with minimum distance path (MDP, 80%) and parallel transport of loader and truck with MDP (78%) were ranked the highest, and single-bale central grouping the lowest (29%) among 19 methods studied. The MDP was found significantly more efficient (4%–16%) than the baler path. Simplistic methods, namely a direct triple-bale loader with MDP (64%–66%), or a loader and truck handling six bales running parallel with MDP (75%–82%) were highly efficient. Great savings on cumulative distances that directly influence time, fuel, and cost were realized when the number of bales handled was increased or additional equipment was utilized.

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http://dx.doi.org/10.1016/j.biombioe.2014.03.013
0961-9534/Published by Elsevier Ltd.

1. Introduction

The common adage "Field to Factory" used in connection with biomass logistics sounds like a simple point-to-point transportation of well-packaged biomass. But a closer look at the biomass distribution for collection reveals a different situation. Although, a "factory" can be considered as a point destination, the biomass on the field, even after consolidation into bales, is a dispersed source. These bales need to be aggregated (collected and transported) to a field-edge stack or field storage to be considered a point source of biomass.

As such, baling is an important postharvest operation because baling of biomass material helps in collection and preservation of biomass as well as clearing the field for subsequent cropping operations. Round bales can be made, left on field, and transported later, uncoupling the harvest and infield transportation operations, which offers a significant advantage [1]. In the field, however, the bales are dispersed (Fig. 1) and hinder future agricultural operations and potential crop regrowth, if not aggregated in a timely manner. Bales left on field too long will damage the plants under them, while the bales themselves lose their integrity, become difficult to handle, and lose significant dry matter [2,3]. Usually, the bales will be moved to a field-edge stack before being transported to a secured storage location or transported to other facilities or to a feedlot for local consumption. Thus an efficient aggregation of bales with the least total distance involved is a goal of producers and bale handlers.

Most of the biomass logistics analyses have concentrated on transporting biomass from the field to proposed processing facilities, considering "field" as a point source of biomass with biomass made into several forms (e.g., pellets, briquettes, bales). Elaborate logistics models of biomass supply to biorefinery have been developed and implemented [4–8]. As these models address biomass supply to a processing facility as a whole, detailed infield bale aggregation was beyond their scope or simplistic methods were assumed for this minor subcomponent. Some of the biomass logistics analyses have been location specific, for instance, biomass transport model to a power plant in India [9], and rice straw biomass for power generation in Thailand [10]. However, literature exclusively on infield biomass logistics is very limited.

Grisso et al. [11] developed a MATLAB interface and program to calculate a logistical pattern of removing round hay bales from a field to storage as a "students' tool" to train students on the timing, distance and pattern of moving, handling and storing round bales. The students developed a loading pattern for a self-loading bale wagon. This system was used to deliver round bales from satellite storage locations to a proposed biorefinery plant [12]. In their study, the bales were assumed randomly placed, collected in batches, and cumulative distances involved were calculated geometrically.

The major component activities of infield bale aggregation are collection of bales into sub-groups and transportation to a field-edge stack or storage using various bale handling equipment. Several scenarios emerge for the various possibilities of aggregation (sub-grouping before field-edge stack transport), loading, and transport involving different equipment (e.g., bale loaders, bale wagons, bale pickers), strategies (e.g., direct transport by loaders, grouping bales and transport, parallel run of baler and truck, bale pickers), and collection paths (e.g., baler and minimum distance). Other factors that influence the aggregation logistics are the crop species handled, area and shape of field, biomass yield, mass of bale, swath width, random variation between the distances of the bales, as well as the economics involved in all the scenarios.

The cumulative transport distance in aggregating bales in a given area directly quantifies the effort involved in this operation. This total distance also serves as an indicator of the time involved and the fuel consumed (energy), hence influences equipment selection and overall economics of the operation. The point of interest in this research is determining the total bale transport distances for various possible scenarios.

The present paper proposes to mathematically simulate the action of a baler to generate the layout of bales on the field, and statistically evaluate and rank the various bale aggregation scenarios. The total distance involved is calculated as the sum of Euclidean distance between the bale and a field-stack or between bales using the analytical distance formula for all bales in the field based on the selected scenario.

Thus the objectives of this research are: To simulate the action of the baler and determine the ideal and random layout of bales; model bale aggregation scenarios and determine the total aggregation distances; statistically determine the effects of field size, number of bales handled, field shape, biomass yield, swath width, bale layout, and collection path on bale aggregation; and rank the considered bale aggregation methods.

Fig. 1 – Biomass bales dispersed on a field after baling. Inset: Bales brought to field-edge stack.

2. Methods

2.1. Ideal field layout of bales

Biomass quantity collected by a baler from the windrow is a function of the desired bale size and bulk density of biomass material. This biomass amount will directly influence the windrow length used in making the bale. The action of the baler can be summarized as (Fig. 2): (1) After collecting the required biomass, it finishes the baling by wrapping or tying operation and ejects the bale; (2) Continues the operations and makes the next bale in the same row; (3) If a row ends before sufficient material is collected to form a bale, the collection is continued after turning back into the next row and proceeding in an opposite direction; and (4) The cycle of operations continue. Thus, baling the biomass along the rows and covering the entire field will leave bales on the field in a specific pattern (Figs. 1 and 2).

2.2. Evaluation of bales field location coordinates

The number of bales produced on a given field can be calculated from field and swath dimensions (Fig. 2). The total length of available swath from field dimensions is:

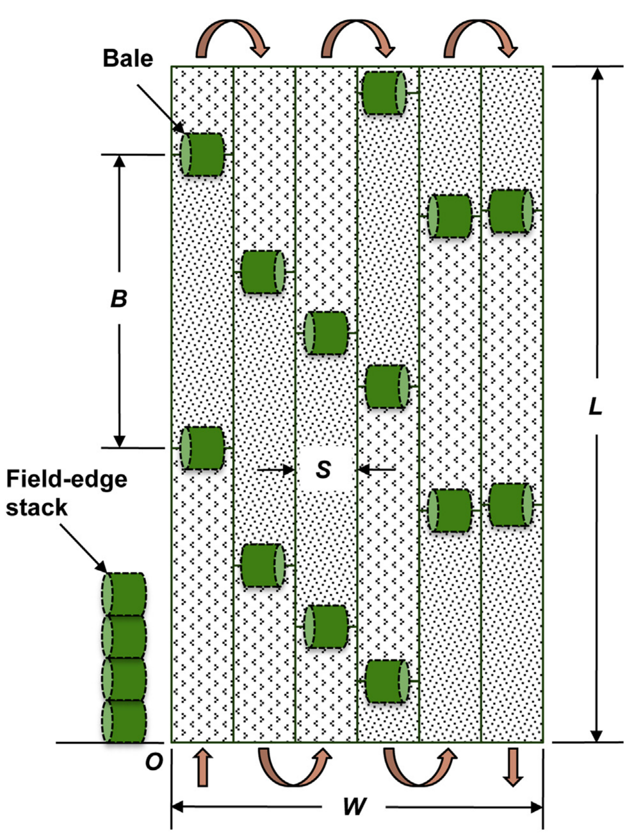


Fig. 2 – Schematic diagram showing the field layout, swath width, path of baler, bale collection length, and the bale drop location.

$$L_s = \frac{W}{S} \times L \quad (1)$$

where, L_s is the total length of swath (m); W is the field width (m); L is the field length (m); and S is the swath width or spacing between windrows (m).

Using (Eq. (1)), the total number of bales produced in a given size of field is:

$$N = \frac{L_s}{B} \quad (2)$$

where, N is the total number of bales produced (integer); and B is the windrow length required for a bale (m).

Alternatively, the above parameters can also be obtained from the basic information, such as the area of the field, field aspect ratio, biomass yield, mass of bale, and swath width as:

$$L = \sqrt{A \times R_{LW}} \quad (3)$$

$$N = \frac{A \times Y_{ha}}{M_b} \quad (4)$$

$$B = \frac{A_{ha}}{S \times (Y_{ha}/M_b)} \quad (5)$$

where, A is the field area (ha); R_{LW} is the length to width aspect ratio of the field (decimal); Y_{ha} is the dry biomass yield per hectare (Mg); M_b is the bale dry mass (Mg); and A_{ha} is the square meter equivalent of a hectare area (m^2).

The layout of bales on the field can be visualized as a packed ribbon having of length L_s with successive alternating loops at the edges that are swath width apart. This random looking pattern of bale layout (Fig. 2) is actually an evenly spaced bale on the ribbon when unwounded and made straight. Location of any bale in terms of the number of field lengths is:

$$L_i = \frac{N_i \times B}{L} \quad (6)$$

where, L_i is the bale location in field lengths (decimal); and N_i is the number of the ith bale (integer).

Since bales are moved from their original location to field-edge stack or storage locations, it is essential to know the field coordinates of the bales for transportation calculations. The bale's x-coordinates will vary simply based on the number of windrows, and y-coordinates will vary with the number of windrow and travel direction of the baler. From the layout dimensions of field (Fig. 2) and bale location (Eq. (6)), the x- and y-coordinates of the bales are calculated as follows:

$$x_i = (L_i \text{ div } 1) \times S + (S/2) \quad (7)$$

$$y_i = \begin{cases} \text{If } (L_i \mathbf{div} 1): & \text{even} \\ \text{Direction}: & \text{forward} \\ \text{Coordinate}: & \mathbf{frac}\,(L_i, 1) \times L \\ \text{If } (L_i \mathbf{div} 1): & \text{odd} \\ \text{Direction}: & \text{return} \\ \text{Coordinate}: & (1 - \mathbf{frac}\,(L_i, 1)) \times L \end{cases} \quad (8)$$

where, x_i and y_i are the coordinates of the ith bale; and '**div**' and '**frac**' operators find the quotient and fractional parts of L_i when divided by 1.

In this study, we assumed that the swath width (S) reflects the bale row spacing and the harvester lays the cut crop as narrow windows for baling. This means that during bale aggregation, the baler is assumed to simply follow the harvester. The application of rake or merger, a common swath tending equipment, that may combine two or more windrows into one, was not considered in this study directly. Even though rake/merger application increases S, it decreases bale spacing in a row (B), the number of bales formed is constant as the biomass handled is the same. Thus, the rearrangement of bales layout due to raking is not expected to change the aggregation methods ranking, as all methods are compared to the "control" using a constant number of bales. However, the effect of rake/merger can be accounted indirectly in the developed program as outlined later (Section 3.1).

2.3. Randomness in bales layout

Variations always exist in the amount and uniformity of swathed material in windrows in actual fields. These variations will affect the windrow length required for bale making (B), which in turn will result in a bale layout pattern differing from the ideal layout.

For lack of field data on spatial variability of biomass in windrows and the combined effect of machine performance resulting in random layout of bales, a reverse approach of assuming a random variation in B up to 20% and observing the resulting layout was followed. JAVA's "*java.util.Random*" class "Gaussian" method generates random numbers from a normal distribution with a mean of 0.0 and a standard deviation (σ) of 1.0 for each bale. With appropriate scaling (3σ giving 99.74% confidence interval) and assumed limit of random variation, the ± values were generated. For example, for a 3σ and a 15% random limit, B takes normally distributed random values in the range $0.85B \le B \le 1.15B$. The various bale aggregation scenarios that can be applied to the ideal layout are equally applicable to the random layout and studied for performance.

2.4. Calculation of transport distances

The one-way transport Euclidean distance of a bale from its original location to another destination is calculated from the geometrical distance formula as:

$$D_{i\rightarrow p} = \sqrt{\left(x_i - x_p\right)^2 + \left(y_i - y_p\right)^2} \quad (9)$$

where, $D_{i\rightarrow p}$ is the one-way distance from any bale location (i) to a fixed stacking location (p) (m); x_i, y_i are the coordinates of bale at i; and x_p, y_p are the coordinates of the destination p.

Eqs. (1)–(9) and randomness on B will be used to determine the number of bales, their location and coordinates, and distance of transport between two points of interest. The total distance of aggregation is the sum of all distances (Eq. (9)) to account for loading and transporting operations that bring the bales to a field-edge stack or storage locations.

A two-way transport distance of a bale from its original location to another location is twice the distance obtained from Eq. (9) ($D_{p\rightarrow i} + D_{i\rightarrow p}$). Eq. (9) can also be used for multiple bale transport by appropriate closed network of paths (Fig. 2). For example: a two-bale loader transporting bales at locations, say, '8' and '9' to 'p' will have the total transport distance of $D_{p\rightarrow 8} + D_{8\rightarrow 9} + D_{9\rightarrow p}$ with appropriate coordinates. The point 'p' can be the origin representing the field-edge stack location or the center of the field for sub-grouping of bales or feedlot location. Thus, conceptually the field-edge stack may equally represent a feedlot or any on-farm temporary storage location.

2.5. Bale collection and transport equipment

Bale aggregation scenarios can be divided into two categories based on whether a multiple bale transport arrangement is included or not. The scenarios will also depend on the type of equipment used in collection and transport, the method of grouping the bales, and the path of bale collection for transport to field-edge stack.

For round bales, the types of bale collection equipment (loader/grapple/spear) considered (Fig. 3) are: single-bale loader – L1, two-bale loader – L2, and three-bale loader – L3. The transport equipment (bale wagon) considered are: six bale wagon – W6, 12 bale wagon – W12, 26 bale wagon – W26, 30 bale wagon – W30, and Cundiff and Grisso [13] a concept design 32 bale wagon – W32.

The other categories of advanced bale handling equipment that produce combinational operations are: bale accumulator – attached to baler that collects bales and unloads them as subgroups (A3) for later transport, and self-loading bale picker trailer – follows the path of the baler and picks and collects the bales and transports them to the field-stack and is capable of handling 6, 10 and 14 bales (A6, A10, and A14). These advanced bale pickers combine the activities of bale loader and bale transport wagon. Although specific equipment restricts the number of bales handled, for the study bales from 1 to 32 were applied to all methods and strategies expect for direct loader methods.

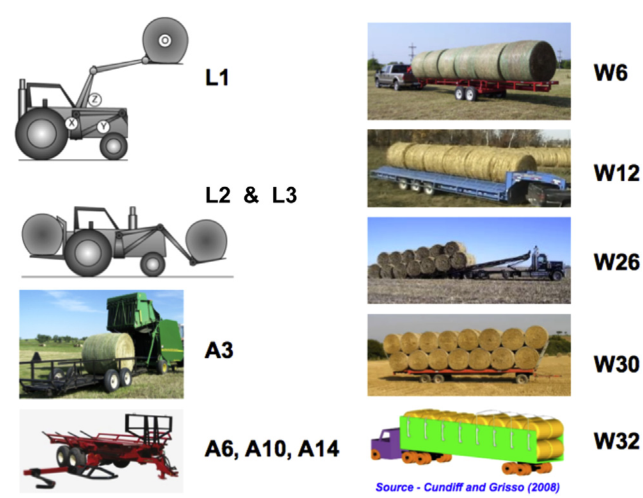


Fig. 3 – Types of bale loaders, transporting wagons, and advanced bale handling equipment; L, W, and A represent loader, wagon, and advanced bale handling equipment respectively, and the numerals indicate the number of bales handled; source of some inset pictures is Google-images.

2.6. *Scenarios of bale collection and transport*

Three types of bale collection and transport strategies (Fig. 4) considered in the study are: (1) Direct collection and transport to the field-edge stack using collection equipment (DT), (2) Centralized grouping using collection equipment and transport to the field-edge stack using transport equipment (CG), and (3) Sub-grouping using collection equipment and transport to the field-edge stack using transport equipment (SG).

The strategies, other than direct transport (Fig. 4a), use either the loader (Fig. 4b and c) or bale accumulator (Fig. 4e) to make subgroups of bales that will be transported back to a field-edge stack by bale wagons. With the parallel run method, the loader loads the bales on to a parallel running self-propelled truck/wagon (Fig. 4d), or bales are hauled by the loader-tractor itself. Bales are usually loaded on bale wagons using the loaders. However, the self-loading bale picker picks up bales and transports them to the field-edge stack (Fig. 4f), eliminating the necessity of the bale loader. To learn about the equipment and aggregation methods being followed by them, interviews were conducted with four local farmers/ranchers of Mandan, ND that handle bales.

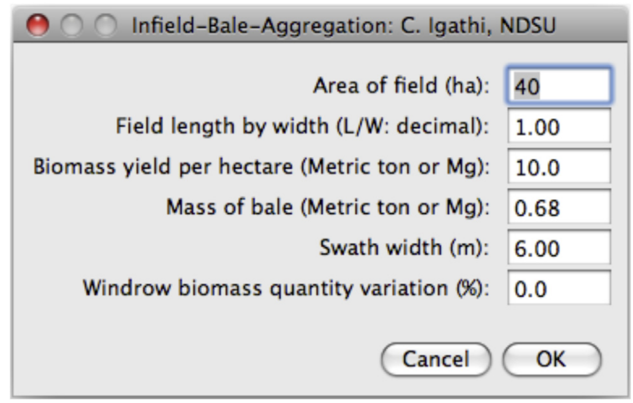
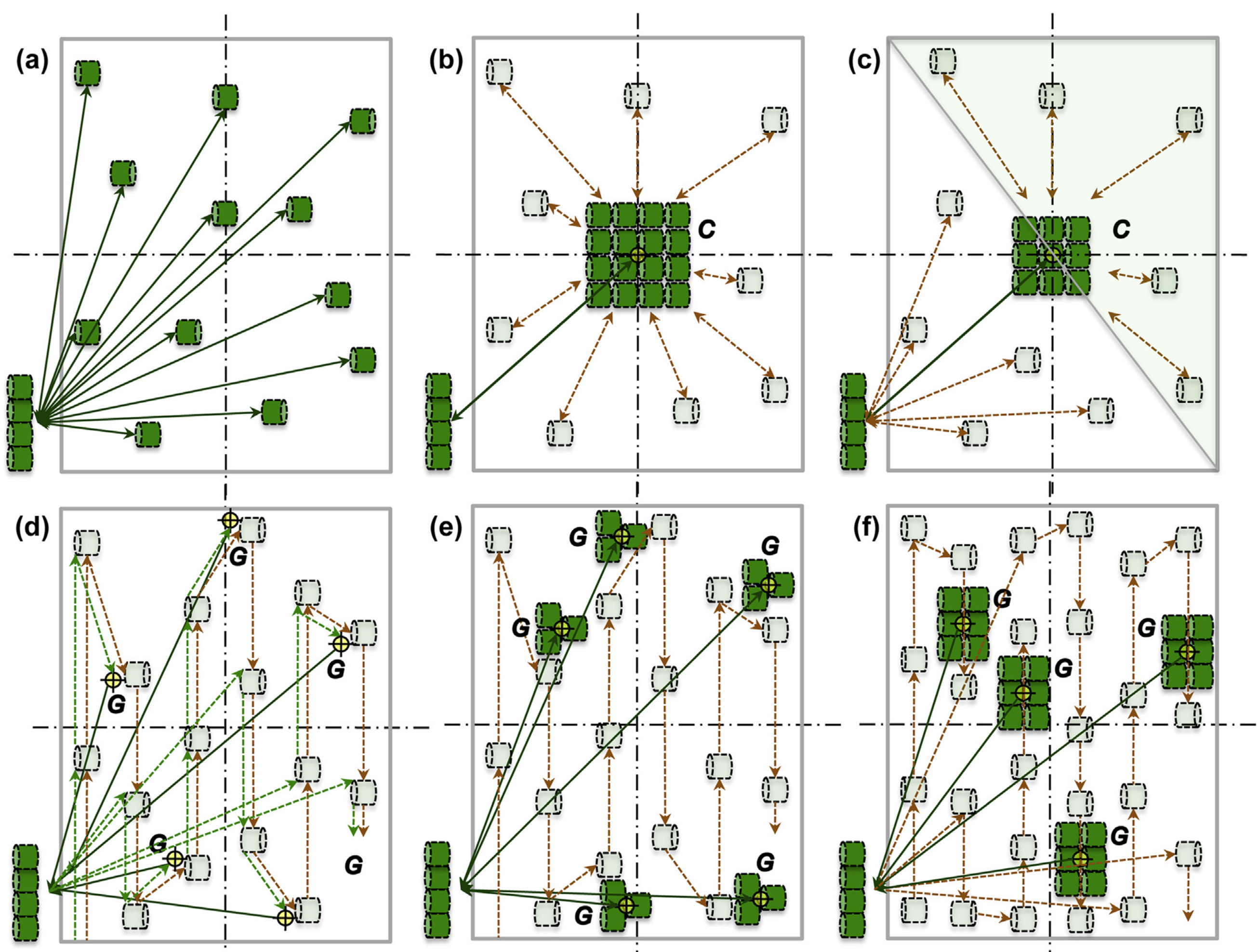


Fig. 5 – The front panel of infield bale aggregation program.

Other common practices used for stacking the bales are leaving a few stacks of bales distributed on field itself or making a few rows of bales along the field length. These distributed bale stacks should be eventually moved away for final utilization. In this study, we have not considered such



(a) Direct loader; (b) Central grouping + transporter; (c) Diagonal grouping + transporter; (d) Parallel run of transporter; (e) Bale accumulator sub-grouping + transporter; (f) self-loading trailer and transport; *C* – central group; *G* – subgroups; ⟷ – transport to edge stack; ⇠⇢ – loader transport to bales or groups; ⇠⇢ – transporter run to bales

Fig. 4 – Bale collection and transport strategies.

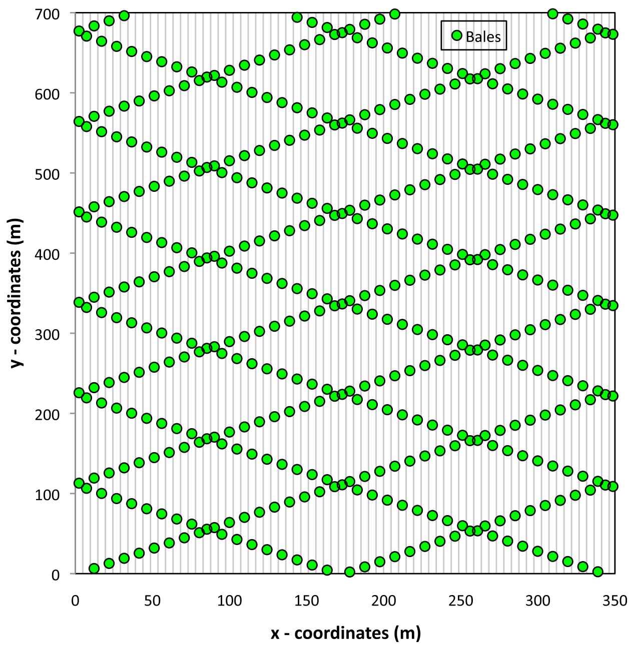


Fig. 6 – Theoretical layout of bales in a field showing a diamond-pattern.

stacks left in the field, but the analysis remains the same by appropriately redefining the field boundaries for the model.

It should be noted that the collection equipment will also perform transportation, but the transportation equipment needs to be loaded by the collection equipment. The SG strategy is similar to running a bale wagon in the field between the rows of bales and loading them for transport back to the stack. This involves two pieces of equipment and two operators. The path of bale collection also influences the logistics performance.

2.7. *Simulation of bale aggregation methods*

Bale aggregation simulation was performed knowing the bale coordinates on the layout and the type of equipment used. The collection path can either be (a) *baler path* (BP)—following the baler movement pattern (Fig. 2) of running parallel to field boundaries and turning back after reaching the other boundary and collecting bales along the way (Fig. 8) or (b) *minimum distance path* (MDP)—locating the shortest distance from a starting point to the next bale every time (Fig. 8); the equipment collects the nearest bale first and from there the next nearest bale and so on. For operators, it is easier to follow the BP for bale collection than MDP, as the latter involves constant judgment in locating the next nearest bale.

For the simulation approach, BP is simply accessing the bale locations in the sequence they were stored in the

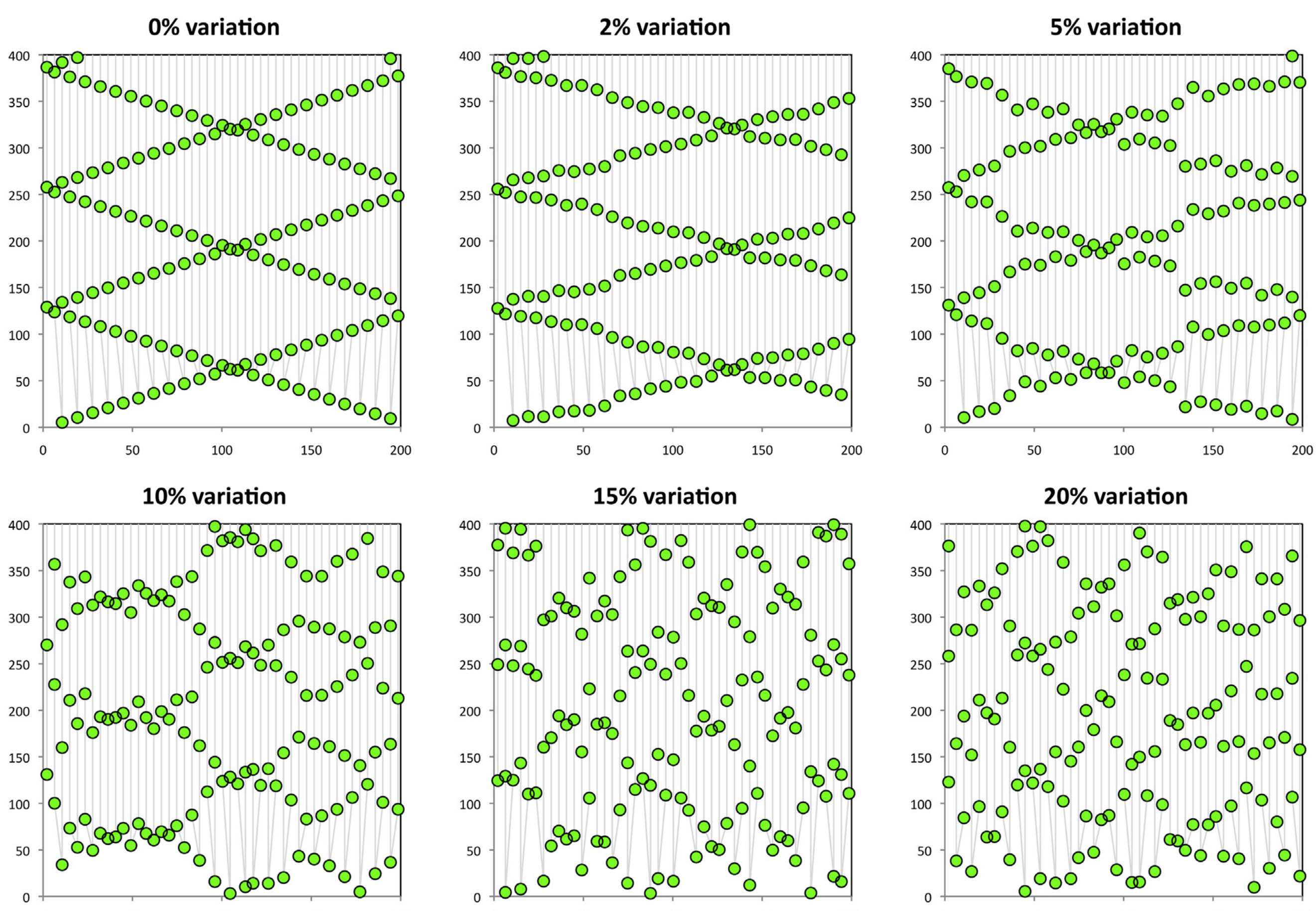


Fig. 7 – Randomness in bale layout of a section of field of 40.5 ha rectangular field (L/W = 2.0, biomass yield = 12.4 Mg/ha, mass of bale = 0.68 Mg, swath = 4.88 m, x and y axes are distances in m).

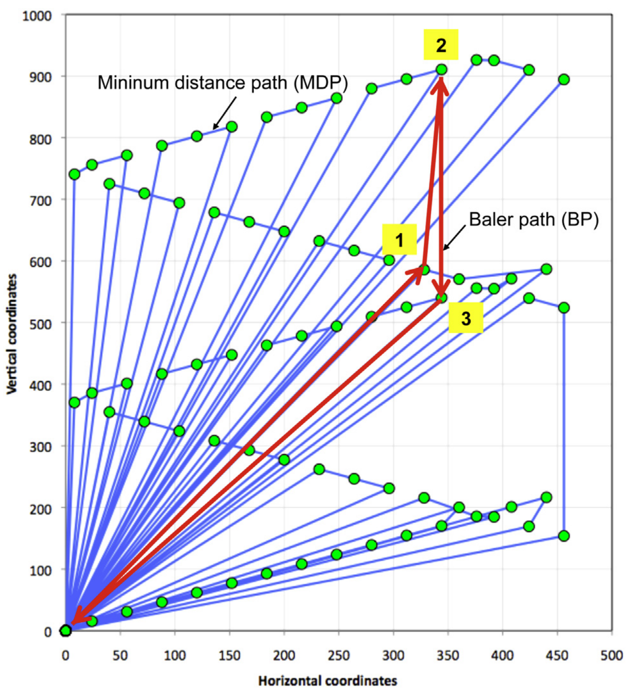


Fig. 8 – Baler path *vs* minimum distance path.

coordinate arrays. While the MDP goes though the bale location arrays and finds the next nearest bale by comparing the distances of all the bales from a point of interest, and finding the minimum distance every time. A simple brute-force method of finding the minimum distance with a fixed array of n elements takes $n \times n$ search operations. But in the simulation, we used an efficient "linked-lists" approach from JAVA class "*java.util.LinkedList*" that contains several methods for lists manipulation. Use of linked lists allowed for removal of elements after they were identified as the minimum, and this progressive removal reduced the number of search operations. Searching for the minimum using linked lists of n elements requires only $n \times (n + 1)/2$ operations, which is about 49.5% reduction from the no-replacement fixed array search method. Although the mathematical method finds the exact nearest bale, the operator in the field might find it by "eyeball" search, which is not expected to deviate much from the mathematical solution. The MDP is applicable to all equipment but the bale accumulator, which is attached to the baler and is forced to follow the baler.

For the simulation, the field-edge stack is assumed to be the origin (lower left corner) with coordinates of $x = 0$, $y = 0$ and the field lies in the first quadrant. This assumption considers that for each run, the equipment starts from the origin, follows a selected collection path and strategy, and returns to it after collecting the specified number of bales. This assumption makes it easier for calculation; however, in reality, when bales are brought to the stack, they occupy a certain area and their locations will deviate from the origin coordinates. This deviation, when compared to the field dimensions, was considered negligible. Furthermore, the deviation is inconsequential as the deviation is applicable to all bale aggregation scenarios and the study only compares the various scenarios with the control. The list of bale aggregation methods considered, their nomenclature used in the study, and a brief description are presented in Table 1, from which the various methods can be understood. For example, the "Cen3Min" method first subgroups the bales at the field center, using a loader that carries three bales ($L = 3$) simultaneously, following the MDP collection strategy (Fig. 8), and later using a wagon of various capacity ($W = 1$–32 bales) to transport the bales to the field stack.

Table 1 – Brief description of bale aggregation methods studied.

Methods nomenclature	Description (bale handling information and figure reference)
Direct1[a] (control)	Direct aggregation by loader along BP; ($L = 1$ bale; Fig. 4a)
Direct2[a]	Direct aggregation by loader along BP; ($L = 2$ bales; Fig. 4a)
Direct2Min[a]	Direct aggregation by loader along MDP; ($L = 2$ bales; Fig. 4a)
Direct3[a]	Direct aggregation by loader along BP; ($L = 3$ bales; Fig. 4a)
Direct3Min[a]	Direct aggregation by loader along MDP; ($L = 3$ bales; Fig. 4a)
Cen1	Central subgrouping & aggregation along BP; ($L = 1$; $W = 1$–32 bales; Fig. 4b)
Cen2	Central subgrouping & aggregation along BP; ($L = 2$; $W = 1$–32 bales; Fig. 4b)
Cen2Min	Central subgrouping & aggregation along MDP; ($L = 2$; $W = 1$–32 bales; Fig. 4b)
Cen3	Central subgrouping & aggregation along BP; ($L = 3$; $W = 1$–32 bales; Fig. 4b)
Cen3Min	Central subgrouping & aggregation along MDP; ($L = 3$; $W = 1$–32 bales; Fig. 4b)
Dia1	Diagonal subgrouping & aggregation along BP; ($L = 1$; $W = 1$–32 bales; Fig. 4c)
Dia2	Diagonal subgrouping & aggregation along BP; ($L = 2$; $W = 1$–32 bales; Fig. 4c)
Dia2Min	Diagonal subgrouping & aggregation along MDP; ($L = 2$; $W = 1$–32 bales; Fig. 4c)
Dia3	Diagonal subgrouping & aggregation along BP; ($L = 3$; $W = 1$–32 bales; Fig. 4c)
Dia3Min	Diagonal subgrouping & aggregation along MDP; ($L = 3$; $W = 1$–32 bales; Fig. 4c)
Para	Parallel run of loader and wagon aggregation along BP; ($W = 1$–32 bales; Fig. 4d)
ParaMin	Parallel run of loader and wagon aggregation along MDP; ($W = 1$–32 bales; Fig. 4d)
Acc	Bale accumulator aggregation along BP; ($W = 1$–32 bales; Fig. 4e)
Picker	Advanced bale picker aggregation along BP; ($W = 1$–32 bales; Fig. 4f)
PickerMin	Advanced bale picker aggregation along MDP; ($W = 1$–32 bales; Fig. 4f)

[a] Fixed number of bales, hence limited data unlike other methods. BP – baler path (Fig. 8). L – loader, used to pick bales for loading as well as transporting, the integer represents the number of bales handled simultaneously. MDP – minimum distance path (Fig. 8). W – wagon, exclusively used for transporting bales. L and W combination means both equipment used in the method.

2.8. *Statistical data analysis*

SAS [14] macro *%mmaov* was used [15] to perform mean separation analysis to determine the effect of field parameters and rank aggregation methods. Also a Student's *t*-test was applied to find the statistical difference between BP and MDP. The possible percent differences from the "control" observed on analysis (negative quantity) were converted to positive values for logarithmic transformation in macro *%mmaov*.

3. Results and discussion

3.1. *Infield bale aggregation program*

A computer program in JAVA was developed to calculate the bale layout (ideal and random) locations, simulate various aggregation scenarios involving combinations of equipment and collection methods, and to evaluate the percent deviation of methods with reference to the control (single-bale loader method). The front panel of the program (Fig. 5) takes in various inputs that includes variation in field area and shape, biomass yield, mass of bale, swath width, and variation for random bales layout. The effect of rake/merger, which alters the normal swath width, can be accounted in the program indirectly by feeding the final merged windrow spacing for the "Swath width" input field (Fig. 5). If the percent windrow material variation was set to the default 0.0, then the layout considered will be "ideal" and any other positive value makes a layout random and analysis performed accordingly.

3.2. *Theoretical layout of bales on field*

A theoretical layout of bales was calculated using the program assuming a field area of 40.5 ha (100 ac), length by width ratio (L/W) of 2.0, biomass yield of 12 Mg/ha (5 Mg/ac), bale mass of 0.68 Mg, and swath width (S) of 4.9 m (16 ft), windrow biomass quantity variation of 0%. The calculated results were field length (L) = 900 m, field width (W) = 450 m, number of bales = 735, and bale collection length (B) = 112.7 m. A section of field showing the theoretical layout of bales is shown in Fig. 6. This theoretical layout displays inclined lines connecting bales running parallel on both directions making a "diamond-pattern". It is expected that any variation of B will make this ideal pattern deviate.

3.3. *Random layout of bales on field*

Differing random limits of variation generate random bale layouts. Bale layout simulation for a 40.5 ha field, with the other parameters the same as in the theoretical layout (Section 3.2), was performed and the resulting sections of bale layout were plotted (Fig. 7) for visualization.

The 0% variation represents the theoretical layout showing the perfect "diamond-pattern". Increasing the random variation limit introduced random ripples with proportional magnitude, but the diamond-pattern is recognizable still at 2% and 5%. Further increase in variation limit to 10% squeezes diamond-pattern length and more patterns were accommodated, but a geometrical pattern is not recognizable. From a variation limit of 15%, a regular pattern was indistinguishable. The 20% variation also substantiates this observation with a clear random bale layout. Based on these results, it can be concluded that above 10% variation a random pattern of bale layout emerges. Further study on the typical infield variation is required for comparison.

3.4. *BP vs MDP*

Following the simulation of bale collection paths described earlier (Section 2.7), direct three-bale loading and transportation paths are shown graphically (Fig. 8). It can be seen that the MDP picks the nearest bale, and this in an ideal layout means collection along the "sides" of the diamond pattern. While the BP method starts from the first bale [1], picks the bale above [2] on the BP, and comes back down to the next bale [3], even though the first [1] and the last [3] bales were closer. It can be readily observed that the MDP will be more efficient than the BP method.

With BP, a vertical line divides the cleared area, towards the infield stack, and the area with bales; while with MDP a circular arc with the infield stack as the center divides these two areas. The simulation shown (Fig. 8) will also work for any random bale layout (Fig. 7), and the lines shown connecting the bales in the random layouts depict the BP method.

3.5. *Common observation on results*

Sample output generated by the bale aggregation program for a 40 ha field of rectangular shape (L/W = 2.0) showing various aggregation scenarios performances with reference to the control against the number of bales handled per trip is given in Fig. 9. Outputs also include overall results, such as field dimensions, number of bales, direct aggregation total distance by control method, total distance and percentage difference with the control method and direct double and triple aggregation, along with results of various aggregation scenarios considered. It should be noted that the MDP applies to all scenarios of handling more than one bale handled at a time, hence is not applicable to the single-bale loader as well as bale accumulator.

Three out of the four farmers interviewed noted that they did not have additional equipment and they use only a single-bale loader to collect and transport bales. Thus, the control method is the most prevalent among farmers because of low input and cost involved. Because of this, there are opportunities to improve upon the existing method of bale aggregation. Even simple attachments such as bale spears/spikes or a grapple that increases the bale handling from one to two or three gives substantial reduction of total collection distance from the control. For example, >40% and >54% reduction for BP and >47% and >64% for MDP is achievable, respectively, for two and three-bale direct loaders (Fig. 9) from the control method.

Results also show the effect of the number of bales (N) on different scenarios varying from 1 to 32. One bale operation was included, though not practical in many scenarios, to understand how this extreme case compared with others. With multiple bale handling methods (e.g., Cen2, Cen2Min, Cen3, etc.), the single base operation (N = 1) applies to only the transport from the grouped location to the field-edge stack. Some of these results will have a positive difference from the control method (Fig. 9).

Results of all scenarios showing percent deviation from the control for two areas, such as 40 and 259 ha are plotted in Fig. 10. It can be seen that the trends of aggregation scenarios for both areas were similar, but close observation indicate that increased area producing insignificant performance

Infield bale aggregation program outputs

Area of field (ha) = 40
L/W = 2.0
Biomass yield per ha (Mg) = 10.0
Bale mass (Mg) = 0.68
Swath width (m) = 6.0
Biomass windrow material variation (%) = 0.0
Layout = Ideal

Total area (m^2) = 400000
Field length (m) = 894.4
Field width (m) = 447.2
Number of bales = 588
Bale pick length (m) = 113.3
Field center location (x, y): = 223.61, 447.21 m
Number of lower and higher bales are: 298 and 290; Missed bales = 0

Direct single bale transport (m) = 623394 (control)
Direct double bale transport (m) = 341869;
Percent of reference (%) = -45.2
Direct triple bale transport (m) = 248284;
Percent of reference (%) = -60.2
Direct double bale transport–MDP (m) = 318768
Percent of reference (%) = -48.9
Direct triple bale transport–MDP (m) = 216162
Percent of reference (%) = -65.3

Central - single – Cen1

N	D (km)	P (%)
1	899.7	44.3
2	605.7	-2.8
3	507.7	-18.6
4	458.7	-26.4
6	409.7	-34.3
8	385.7	-38.1
10	370.7	-40.5
12	360.7	-42.1
26	334.7	-46.3
30	331.7	-46.8
32	330.7	-47.0

Central – double – Cen2

N	D (km)	P (%)
1	774.3	24.2
2	480.3	-23.0
3	382.3	-38.7
4	333.3	-46.5
6	284.3	-54.4
8	260.3	-58.3
10	245.3	-60.7
12	235.3	-62.3
26	209.3	-66.4
30	206.3	-66.9
32	205.3	-67.1

Central – double – Cen2Min

N	D (km)	P (%)
1	750.0	20.3
2	456.0	-26.9
3	358.0	-42.6
4	309.0	-50.4
6	260.0	-58.3
8	236.0	-62.2
10	221.0	-64.6
12	211.0	-66.2
26	185.0	-70.3
30	182.0	-70.8
32	181.0	-71.0

Central – triple – Cen3

N	D (km)	P (%)
1	732.5	17.5
2	438.5	-29.7
3	340.5	-45.4
4	291.5	-53.2
6	242.5	-61.1
8	218.5	-65.0
10	203.5	-67.4
12	193.5	-69.0
26	167.5	-73.1
30	164.5	-73.6
32	163.5	-73.8

Central – triple – Cen3Min

N	D (km)	P (%)
1	701.6	12.6
2	407.6	-34.6
3	309.6	-50.3
4	260.6	-58.2
6	211.6	-66.1
8	187.6	-69.9
10	172.6	-72.3
12	162.6	-73.9
26	136.6	-78.1
30	133.6	-78.6
32	132.6	-78.7

Diagonal – double – Dia1

N	D (km)	P (%)
1	663.9	6.5
2	518.9	-16.8
3	470.9	-24.5
4	446.9	-28.3
6	422.9	-32.2
8	410.9	-34.1
10	402.9	-35.4
12	398.9	-36.0
26	385.9	-38.1
30	383.9	-38.4
32	383.9	-38.4

Diagonal – double – Dia2

N	D (km)	P (%)
1	505.1	-19.0
2	360.1	-42.2
3	312.1	-49.9
4	288.1	-53.8
6	264.1	-57.6
8	252.1	-59.6
10	244.1	-60.8
12	240.1	-61.5
26	227.1	-63.6
30	225.1	-63.9
32	225.1	-63.9

Diagonal – double – Dia2Min

N	D (km)	P (%)
1	480.7	-22.9
2	335.7	-46.2
3	287.7	-53.9
4	263.7	-57.7
6	239.7	-61.6
8	227.7	-63.5
10	219.7	-64.8
12	215.7	-65.4
26	202.7	-67.5
30	200.7	-67.8
32	200.7	-67.8

Diagonal – triple – Dia3

N	D (km)	P (%)
1	452.6	-27.4
2	307.6	-50.7
3	259.6	-58.4
4	235.6	-62.2
6	211.6	-66.1
8	199.6	-68.0
10	191.6	-69.3
12	187.6	-69.9
26	174.6	-72.0
30	172.6	-72.3
32	172.6	-72.3

Diagonal – triple – Dia3Min

N	D (km)	P (%)
1	424.3	-31.9
2	279.3	-55.2
3	231.3	-62.9
4	207.3	-66.7
6	183.3	-70.6
8	171.3	-72.5
10	163.3	-73.8
12	159.3	-74.4
26	146.3	-76.5
30	144.3	-76.9
32	144.3	-76.9

Parallel run - Para

N	D (km)	P (%)
1	685.4	10.0
2	405.0	-35.0
3	311.4	-50.1
4	264.6	-57.6
6	217.3	-65.2
8	194.2	-68.9
10	179.7	-71.2
12	169.9	-72.7
26	143.6	-77.0
30	140.8	-77.4
32	139.4	-77.6

Parallel run - ParaMin

N	D (km)	P (%)
1	633.0	1.5
2	330.4	-47.0
3	229.1	-63.3
4	178.0	-71.5
6	127.3	-79.6
8	102.9	-83.5
10	87.0	-86.1
12	76.6	-87.7
26	50.1	-92.0
30	48.9	-92.2
32	47.6	-92.4

Bale accumulator – Acc

N	D (km)	P (%)
1	686.5	10.1
2	375.1	-39.8
3	271.4	-56.5
4	219.4	-64.8
6	167.7	-73.1
8	141.8	-77.3
10	26.3	-79.7
12	116.0	-81.4
26	88.1	-85.9
30	85.4	-86.3
32	83.1	-86.7

Bale picker – Picker

N	D (km)	P (%)
1	622.3	-0.2
2	341.9	-45.2
3	248.3	-60.2
4	201.5	-67.7
6	154.2	-75.3
8	131.1	-79.0
10	116.6	-81.3
12	106.9	-82.9
26	80.5	-87.1
30	77.7	-87.5
32	76.3	-87.8

Bale picker – PickerMin

N	D (km)	P (%)
1	588.6	-5.6
2	315.5	-49.4
3	215.7	-65.4
4	164.8	-73.6
6	114.2	-81.7
8	89.4	-85.7
10	74.0	-88.1
12	64.0	-89.7
26	37.0	-94.1
30	33.9	-94.6
32	32.6	-94.8

Fig. 9 – Generated bale aggregation logistic scenarios sample output for 40 ha area; *L/W* – length to width ratio; MDP – minimum distance path; *N* – number of bales handled at a time; *D* – total distance of moving all the bales; *P* – percent difference from the control; Table 1 may be referred for methods nomenclature and description.

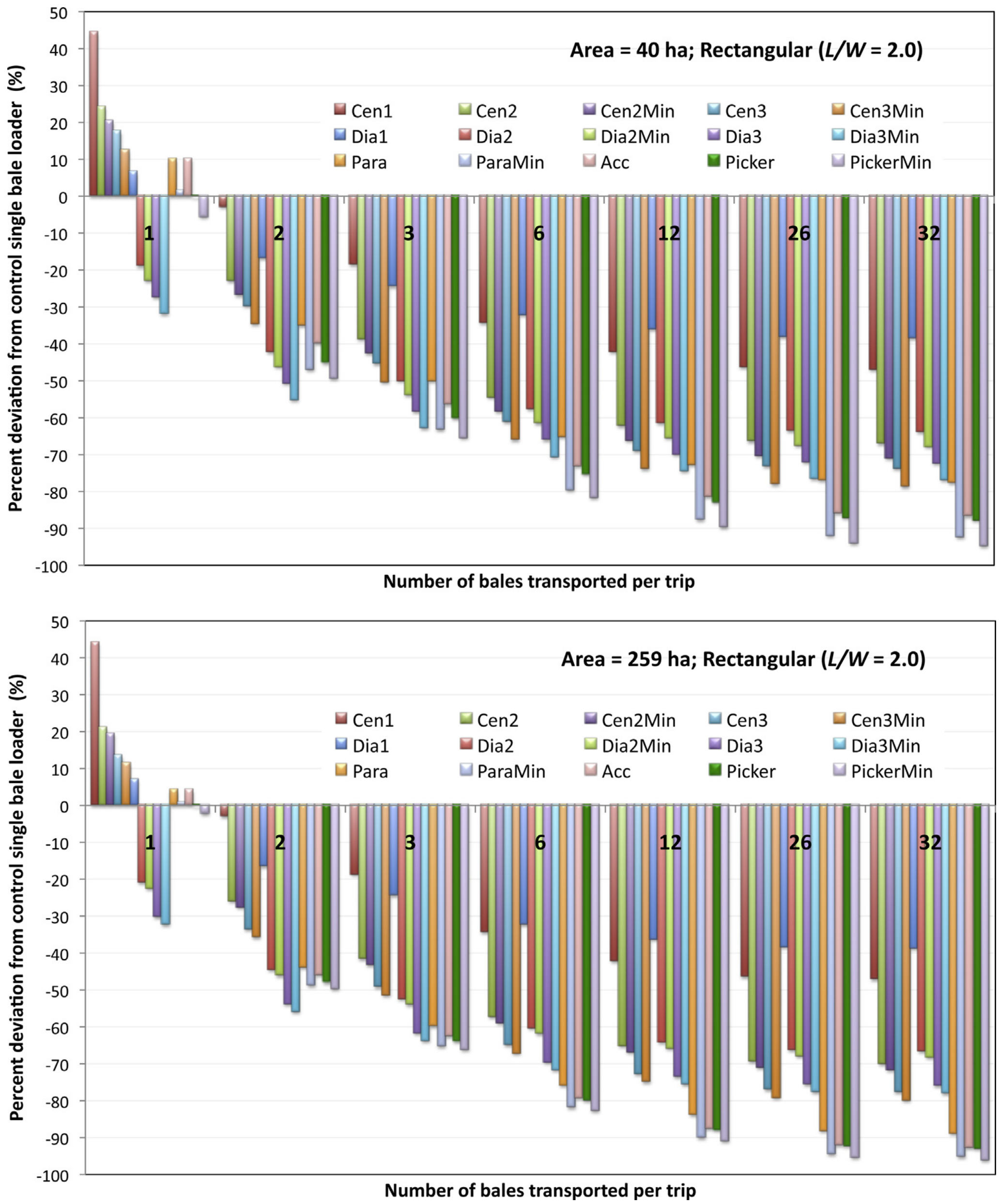


Fig. 10 – Results of comparison of bale aggregation scenarios on two different areas of rectangular fields (biomass yield = 10 Mg/ha, mass of bale = 0.68 Mg, swath = 6 m, ideal layout); Table 1 may be referred for explanation of legends.

improvement. Similar trends were observed among the various methods when closely related areas were considered. It can be seen that central grouping with $N = 1$ (Cen1, Cen2, Cen2Min, Cen3, and Cen3Min) make a positive deviation from the control. The reason is these methods involve negative transportation distances of moving the bales, typically near the field-edge stack, towards the field center and later bringing them back again. Such negative bale transport is counter-productive and the central grouping methods involve this. Other methods that produce noticeable positive deviation with $N = 1$ are parallel run (Para) and bale accumulator (Acc). Even though there is no direct negative transport, having the equipment run to cover all the bales following BP and transporting to the field-edge stack doubles the travel distance. However, the reduction obtained by the diagonal grouping methods (Dia2, Dia2Min, Dia3, and Dia3Min) was because of no negative transport as well as more than one bale (2 and 3) being grouped during collection even though only one bale ($N = 1$) was used in transport. The rest of the methods at with $N = 1$, namely parallel run with MDP (ParaMin) and self-loading bale picker (Picker) coincides with the control, while PickerMin produced negative deviation.

Useful total distance reduction from the control method occurs with methods that handle multiple bales at a time beginning with two bales (Fig. 10). As the number of bales handled increase from 2 to 12, there is a steady increase in reduction for all the methods and the trend flattens out after 12 bales. This observation may lead to the conclusion that there is no need to go to large equipment handling more than 12 bales at a time. Even a six bale self-loading picker produces about an 80% reduction from the control. Smaller equipment tends to be lighter, thereby avoiding unnecessary soil compaction in field. They are also less expensive than larger and heavier versions. The results also illustrate that the use of additional equipment with a loader was efficient, and the different reductions produced by different methods were distinct. It can be observed from the results (Fig. 10) that "PickerMin" is the best and "Cen1" is the least efficient method, while "Para" is comparable to "PickerMin" and "Acc" to "Picker" when $N \geq 6$.

A definite reduction in utilizing MDP than the BP method can be observed in all applicable scenarios including direct methods (Figs. 9 and 10). A Student's *t*-test analysis at $\alpha = 0.05$ indicated that all the applicable combinations that had BP and MDP (e.g., Direct2 & Direct2Min, Picker & PickerMin, etc.) were significantly different with $P < 0.0001$. The difference between MDP and BP ranged from 4% to 16% with mean of 6.6 ± 4.0%. This analysis indicates that a simple manipulation of aggregation path with the same set of equipment produces a significant advantage in performance.

3.6. *Effect of shape, swath width, biomass yield and randomness on bale layout*

Effect of various field parameters on percent reduction from control was determined for two areas, such as 24 and 259 ha, with square shaped field ($L/W = 1$), biomass yield of 10 Mg/ha, swath width of 6 m, and ideal layout in general; while varying only the particular field parameter to determine its influence and the results are presented in Table 2. Combined data from all scenarios were analyzed for the individual effects. The mean separation results reveal that the shape of the field (square *vs* rectangle with various levels of L/W, such as 2, 4, and 8) does not affect the outcomes of different scenarios for both the areas. This means the results can be applicable equally to both square and rectangular fields, and possibly to other shapes, as the results are simply comparisons between the control and other methods considered.

Swath width is a reflection of the equipment working width, and its variation from 2 to 15 m in general did not significantly affect the aggregation performance (Table 2). However, the 2 m swath at area of 24 ha only was significantly different from ≥9 m. Thus, gathering two windrows into one and baling will produce similar percent reduction when compared to the control method. Furthermore, a gradually increased performance with increased swath width was observed.

Biomass yield varying from 1 to 40 Mg/ha did not produce significant difference in aggregation performance in general; however, the 1 Mg/ha at 259 ha was significantly different from ≥10 Mg/ha (Table 2). A slight increase in performance with higher yields was again noticed. The lack of significant difference in biomass yield indicates that the analysis could be applied to different crops or to a single crop with different levels of biomass made available for baling.

Although the levels of randomness studied (2%–20%) have produced different random bale layout patterns (Fig. 7), the aggregation performance was not significantly different (Table 2). This means it is immaterial whether the bales are arranged in a regular or random pattern, the aggregation performance percent difference from the control method holds the same.

Table 2 – Effect field parameters on the overall bale aggregation performance.

Field parameter	Value	Unsigned percent deviation estimate means from control method (%)			
		Area 24 ha		Area 259 ha	
		EM ± SE	LG	EM ± SE	LG
Shape (length/width)	1	57.53 ± 0.28	A	61.16 ± 0.29	A
	2	57.54 ± 0.28	A	61.14 ± 0.29	A
	4	57.94 ± 0.28	A	60.92 ± 0.29	A
	8	58.49 ± 0.28	A	60.75 ± 0.29	A
Swath width (m)	2	51.20 ± 0.24	B	58.35 ± 0.26	A
	6	57.53 ± 0.26	AB	61.16 ± 0.26	A
	9	59.03 ± 0.26	A	61.66 ± 0.26	A
	12	59.61 ± 0.26	A	61.90 ± 0.26	A
	15	60.00 ± 0.26	A	62.14 ± 0.26	A
Biomass yield (Mg/ha)	1	54.92 ± 0.24	A	50.97 ± 0.25	B
	10	57.53 ± 0.25	A	61.16 ± 0.27	A
	20	59.86 ± 0.25	A	61.98 ± 0.27	A
	30	60.89 ± 0.26	A	62.27 ± 0.27	A
	40	61.24 ± 0.26	A	62.43 ± 0.27	A
Random variation limit	0	57.53 ± 0.25	A	61.16 ± 0.26	A
	2	57.62 ± 0.25	A	61.14 ± 0.26	A
	5	57.62 ± 0.25	A	61.16 ± 0.26	A
	10	57.60 ± 0.25	A	61.17 ± 0.26	A
	15	57.77 ± 0.25	A	61.17 ± 0.26	A
	20	57.52 ± 0.25	A	61.14 ± 0.26	A

EM ± SE – estimated mean ± standard error estimate; LG – letter group, common letter means are not significantly different ($\alpha = 0.05$).
Data: $L/W = 1$; biomass yield = 10 Mg/ha; mass of bale = 0.68 Mg; swath = 6 m; ideal layout; bales handled = 2–32; and 15 methods (no direct methods). Field parameters varied only to studied field parameters.

Overall, considering the two widely differing field areas (24 and 259 ha), it was observed that the above field parameters did not vary significantly in the studied ranges; except for the smallest values of swath (2 m) and biomass yield (1 Mg/ha) considered at specific field areas. Therefore, it can be concluded in general that these field parameters will not have significant effect on the aggregation performance within the range of areas studied and as well be applicable to other field areas.

3.7. *Effect of area*

Table 3 presents the mean separation results of area and number of bales handled as affected by shapes and bale layout including combined data. Overall, the effect of area on the results was significantly different, but not for similar areas (e.g., 40–259 ha, and 16–40 ha for combined data). However, with the ideal layout, area and shape had no significant effect. The combined data displayed more means (4 groups) than the individual data (3 groups). Field shapes again did not influence the results with a random layout. Based on field areas and shapes, one may conclude that from 40 ha and higher (≥24 ha from random layout subset data), the effect of area is not

Table 3 – Effect of area, number of bales, methods and their ranking as affected by field shapes and bale layouts on aggregation performance.

Parameter	Value/rank	Unsigned percent deviation estimate means from the control method (%)									
		Combined overall		Ideal layout				Random layout			
				Square only		Rectangle only		Square only		Rectangle only	
		EM ± SE	LG	EM ± SE	LG	EM ± SE	LG	EM ± SE	LG	EM ± SE	LG
Area (ha)	259	61.14 ± 0.08	A	61.16 ± 0.26	A	61.14 ± 0.27	A	61.15 ± 0.13	A	61.13 ± 0.13	A
	129	60.48 ± 0.08	AB	60.59 ± 0.26	A	60.44 ± 0.27	A	60.49 ± 0.13	AB	60.45 ± 0.13	AB
	40	58.64 ± 0.08	ABC	58.72 ± 0.25	A	58.66 ± 0.26	A	58.70 ± 0.13	AB	58.56 ± 0.13	ABC
	32	58.28 ± 0.08	BC	58.54 ± 0.25	A	58.25 ± 0.26	A	58.28 ± 0.13	ABC	58.21 ± 0.13	ABC
	24	57.58 ± 0.08	C	57.53 ± 0.25	A	57.54 ± 0.26	A	57.53 ± 0.13	ABC	57.65 ± 0.13	ABC
	16	56.62 ± 0.08	CD	56.61 ± 0.25	A	56.66 ± 0.26	A	56.58 ± 0.12	BC	56.65 ± 0.13	BC
	8	54.71 ± 0.08	D	54.91 ± 0.25	A	54.80 ± 0.25	A	54.60 ± 0.12	C	54.76 ± 0.13	C
Bales	32	70.74 ± 0.09	A	70.71 ± 0.27	A	70.88 ± 0.28	A	70.59 ± 0.13	A	70.86 ± 0.14	A
	30	70.66 ± 0.09	A	70.63 ± 0.27	A	70.79 ± 0.28	A	70.53 ± 0.13	A	70.77 ± 0.14	A
	26	70.11 ± 0.09	A	70.08 ± 0.27	A	70.21 ± 0.28	A	69.97 ± 0.13	AB	70.23 ± 0.14	AB
	12	66.59 ± 0.08	B	66.55 ± 0.26	AB	66.69 ± 0.27	AB	66.46 ± 0.13	ABC	66.69 ± 0.13	ABC
	10	65.38 ± 0.08	BC	65.39 ± 0.26	AB	65.51 ± 0.27	AB	65.26 ± 0.13	BC	65.47 ± 0.13	BC
	8	63.25 ± 0.08	C	63.27 ± 0.25	AB	63.33 ± 0.26	AB	63.15 ± 0.13	CD	63.32 ± 0.13	CD
	6	59.96 ± 0.08	D	59.96 ± 0.25	BC	60.00 ± 0.26	BC	59.86 ± 0.12	D	60.03 ± 0.13	D
	4	53.29 ± 0.07	E	53.36 ± 0.23	CD	53.30 ± 0.24	CD	53.28 ± 0.12	E	53.28 ± 0.12	E
	3	46.47 ± 0.07	F	46.58 ± 0.22	D	46.46 ± 0.23	D	46.48 ± 0.11	F	46.44 ± 0.11	F
	2	30.97 ± 0.06	G	31.36 ± 0.18	E	30.68 ± 0.18	E	31.26 ± 0.09	G	30.66 ± 0.09	G
Method	(1) PickerMin	80.27 ± 0.10	A	80.40 ± 0.31	A	80.34 ± 0.33	A	80.21 ± 0.16	A	80.29 ± 0.16	A
	(2) ParaMin	77.93 ± 0.10	A	78.23 ± 0.31	A	78.15 ± 0.32	A	77.81 ± 0.15	AB	77.93 ± 0.16	AB
	(3) Picker	73.08 ± 0.10	B	72.91 ± 0.30	AB	73.29 ± 0.31	AB	72.87 ± 0.15	BC	73.30 ± 0.16	BC
	(4) Dia3Min	70.20 ± 0.09	BC	70.45 ± 0.29	ABC	70.30 ± 0.31	ABC	70.09 ± 0.15	CD	70.23 ± 0.15	CD
	(5) Acc	69.18 ± 0.09	C	68.89 ± 0.29	ABC	69.49 ± 0.30	ABC	68.85 ± 0.14	CDE	69.49 ± 0.15	CDE
	(6) Dia3	65.27 ± 0.09	D	65.50 ± 0.28	BCD	65.16 ± 0.29[a]	BCD	65.28 ± 0.14	DEF	65.24 ± 0.15	DEF
	(7) Direct3Min[b]	65.23 ± 0.04	a	65.30 ± 0.13	a	65.36 ± 0.12[a]	a	65.16 ± 0.06	a	65.24 ± 0.06	a
	(8) Cen3Min	64.40 ± 0.09	D	64.68 ± 0.28	BCD	64.32 ± 0.29	BCD	64.47 ± 0.14	EFG	64.29 ± 0.15	EF
	(9) Dia2Min	60.92 ± 0.09	E	60.87 ± 0.27	CDE	61.13 ± 0.29	CDE	60.76 ± 0.14	FGH	61.05 ± 0.14	FG
	(10) Para	60.22 ± 0.09	E	59.73 ± 0.27	CDE	60.76 ± 0.28	CDE	59.67 ± 0.13	GH	60.77 ± 0.14	FG
	(11) Direct3[b]	59.20 ± 0.04	b	59.08 ± 0.12	b	59.34 ± 0.12	b	59.03 ± 0.06	b	59.37 ± 0.06	b
	(12) Cen3	58.23 ± 0.09	EF	58.23 ± 0.27	DE	58.22 ± 0.28	DE	58.22 ± 0.13	H	58.25 ± 0.14	G
	(13) Dia2	56.89 ± 0.08	F	57.12 ± 0.26	DE	56.70 ± 0.27	DE	56.97 ± 0.13	H	56.79 ± 0.14	G
	(14) Cen2Min	56.28 ± 0.08	F	56.57 ± 0.26	DE	56.22 ± 0.27	DE	56.35 ± 0.13	H	56.15 ± 0.14	G
	(15) Cen2	51.49 ± 0.08	G	51.55 ± 0.25	E	51.43 ± 0.26	E	51.57 ± 0.12	I	51.42 ± 0.13	H
	(16) Direct2Min[b]	48.70 ± 0.03	c	48.82 ± 0.11	c	48.77 ± 0.11	c	48.65 ± 0.05	c	48.69 ± 0.05	c
	(17) Direct2[b]	44.44 ± 0.03	d	44.31 ± 0.11	d	44.58 ± 0.10	d	44.32 ± 0.05	d	44.56 ± 0.05	d
	(18) Dia1	31.13 ± 0.06	H	31.03 ± 0.19	F	31.18 ± 0.20	F	31.07 ± 0.10	J	31.22 ± 0.10	I
	(19) Cen1	28.88 ± 0.06	I	29.29 ± 0.19	F	28.44 ± 0.19	F	29.33 ± 0.09	J	28.44 ± 0.10	J

EM ± SE – estimated mean ± standard error estimate. LG – letter group, means having a common letter are not significantly different ($\alpha = 0.05$).

[a] The ranking should be interchanged.

[b] The EM ± SE of direct methods were calculated from limited data without number of bales consideration as no transporting wagons are involved. These groups differences were identified by lowercase letter groups and were calculated separately but pooled with other methods for ranking. Table 1 may be referred for explanation of methods nomenclature.

significant, which means the results are applicable to most US farms.

3.8. *Effect of number of bales handled*

Analysis on the effect of the number of bales shows definite differences due to the number of bales handled (Table 3), but closely related groups were not significantly different. For instance, there was no significant difference from 12 to 32 bales when individual shape and bale layouts were considered (Fig. 7). Similarly, the other groups, such as 8–12 bales were not significantly different. However, on the lower side for 2, 3, 4, and 6 bales, the percent deviations in distances were significantly different from one another. This indicates that direct double and direct triple bale handling were significantly more efficient compared to the control method (Fig. 9). Random layout produced more mean groups than the ideal layout (7 *vs* 5 groups). From the observations, it can be concluded that significant differences were obtained when the number of bales handled were on the lower range (1–6), and the differences decrease thereafter with increased number of bales.

3.9. *Ranking of various bale aggregation methods*

The mean separation results ranking the various aggregation methods according to the percentage reduction from the control are presented in Table 3. It was observed that the random layout produced more mean groups than the ideal layout, but within layouts the shapes were mostly not significantly different.

The "PickerMin" method was found as the best (80%) and "Cen1" as the least (29%) efficient methods. It is interesting to note that "PickerMin" and "ParaMin" methods, ranked 1st and 2nd respectively, were not significantly different and belong to the same 1st group. The 3rd and 4th ranked methods were "Picker" and "Dia3Min", respectively and belong to the second group. "Acc" method was ranked behind as 5th as the efficient MDP method is not applicable to this method. The "Dia3", "Direct3Min", and "Cen3Min" methods were ranked 6th–8th, respectively, but their aggregation performance was not significantly different. It is interesting to note that the "Direct3Min" compared well with the "Dia3" and "Cen3Min" methods that involve two pieces of equipment that include bale wagon capable of moving 32 bales. The "Dia2Min" method was ranked 9th ahead of "Para" (10th), as the latter follows the BP that apparently required larger distances than the MDP of "Dia2Min". Among the first ten methods, presence of only five–six letter groups indicates overlap of methods performance. This means most of the adjacent methods, although ranked differently, were not significantly different.

The "Direct3" method was ranked 11th ahead of "Cen3" (12th), because the latter involved negative transport, but the methods ranked from 9th through 12th were not significantly different. Similarly, "Dia2" was ranked (13th) ahead of "Cen2Min" (14th) and "Cen2" (15th) methods due to the negative transport of central grouping methods. Among the direct methods, "Direct2Min" (16th) was ranked ahead of "Direct2" (17th). Finally, the "Dia1" method was ranked 18th and "Cen1" as 19th. Overall, it can be observed that the methods with BP as well as central grouping were ranked below the corresponding MDP and other comparable methods. The last six methods were significantly different based on the combined data (Table 3).

Direct aggregation methods that handled more than one bale involves only one piece of equipment with simple attachments, hence it is cost effective. Mean separation results on direct methods ("Direct2", "Direct3", "Direct2Min", and "Direct3Min") with various field areas also emerged as useful. The observed trend of increased efficiency with increased number of bales simultaneously handled was also observed with these direct methods. Again direct methods that use MDP were better than those that use BP. All four direct methods were significantly different and they were ranked favorably among the other methods (Table 3). "Direct3Min" ranked closely with "Dia3" but significantly ahead of "Para", similarly "Direct3" ranked higher than "Cen3". These results are interesting that the direct methods were ranked ahead of some methods that involve two pieces of equipment. However, the "Direct2Min" and "Direct2" methods were ranked very low (16th and 17th) and were only ahead of "Dia1" and "Cen1", but were about >44% more efficient than the "control" method.

It is worthwhile to note that the "ParaMin" method, when carrying capacities are equal, could achieve a statistically equivalent efficiency (78%) compared to the best performing "PickerMin" (80%). Another useful result is "Direct3Min" produced efficiency (65%) that was not significantly different from "Acc". This also means that comparable efficiencies can be attained without acquiring additional bale handling equipment. Practical recommendations such as a single-bale loader with triple bale handling, a single-bale loader with a parallel run truck handling three and six bales, and a six bale self-loading picker each with MDP produce respective efficiencies of 64%–66%, 60%–65%, 75%–82%, 80%–83% with reference to the single-bale loader control.

3.10. *Total distances involved in bale aggregation*

Results can also be interpreted by plotting total distances involved in bale aggregation with each aggregation method for a selected numbers of bales handled (Fig. 11). Total distances of aggregation display similar trends of the percentage deviation (Fig. 10) but were in the opposite direction. The largest total distance on a quarter section square field area (65 ha) to collect the 955 bales was 1178 km by control method, while the least distance was 118 km by the self-loading picker with 12 bale capacity with MDP. Substantial reduction on distances was observed when the number of bales handled was increased (e.g., Direct1 to Direct2, Bales2 to Bales6), while significant reduction was observed by changes in aggregation paths (BP *vs* MDP; e.g., Dia2 and Dia2Min, Picker and PickerMin).

An application of the results is the assessment of time involved in bale aggregation. From the speed and fuel utilization per unit distance of the equipment, the time involved and fuel consumption, respectively, can be assessed logically as these quantities vary directly with the total distance. A speed of 8 kmph (5 mph), considering the bale loading and the travel with load, is assumed and the time taken was calculated using the results (Fig. 11). It requires 146.4 h (18.3 days at 8 h/day) for "Direct1" method; however, using "Direct3Min" the time is reduced to 50.6 h (6.3 days), while with "PickerMin" method handling 6 and 12 bales may take 26.5 h (3.3 days) and 14.6 h (1.8 days), respectively. A similar approach can be employed to assess the fuel requirement of equipment with their specific fuel consumption data. Time and fuel can be readily correlated to the operational cost of the bale aggregation process. The results (total distances) quickly show how long it takes to complete the bale aggregation process and which method is viable technically and financially. This information gives better insight for farmers and operators and helps them make better management and infield logistics decisions.

3.11. *Recommendations for future equipment development*

We observe that the automatic bale pickers as well as parallel run loader and wagon in MDP had the highest rankings (Table 3), and it is advantageous to develop efficient and compact pickers and wagons. Although some loaders can stack two layers of bales on the wagon, the automatic bale pickers usually stack the bales in one layer. A future possible development is to envision a multiple layer stacking arrangement in the bale pickers, at least for two layers initially. Another possibility is to make the bales to stand on their ends on the bale picker bed, as this orientation will be more efficient than

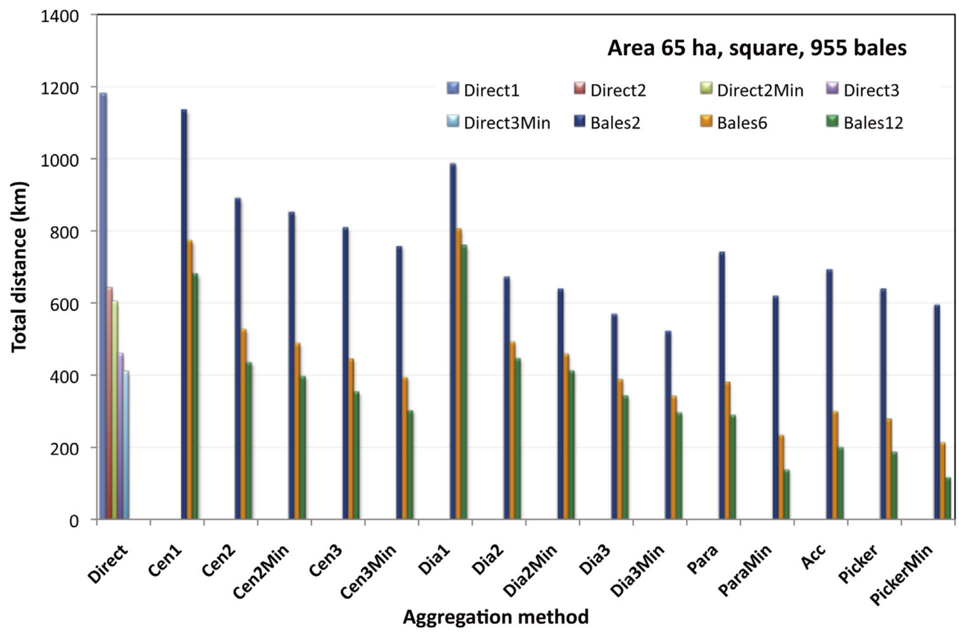


Fig. 11 – Total distances traveled for aggregation of 955 bales on a 65 ha square field (biomass yield = 10 Mg/ha, mass of bale 0.68 Mg, swath = 6 m, ideal layout).

the usual sideways orientation while aggregating the bales, especially in the single layer arrangement.

Future wagons should also be developed to be compact that can handle more bales through better bale stacking arrangements (e.g., multiple layers, bale orientation). It is also necessary to develop the wagons that are lighter using advanced materials or other methods (e.g., increased number of wheels, wider and larger wheels, etc.) so that the soil compaction under the tracks is reduced and require reduced effort to haul.

Bale handling attachments to the loader–tractor can also be improved to allow for multiple layer stacking and bale orientation. In addition, development of simple attachments to the loader–tractor that can handle more bales simultaneously will not only improve aggregation efficiency but will also be an economical option.

3.12. *Recommendations for future research*

Further research work is necessary to rigorously evaluate the economics of all the bale aggregation scenarios involving specific equipment. Such economic analysis, with more realistic time motion data, is expected to change the ranking of different methods arrived at thus far with Euclidean cumulative distances (Table 3). However, the results of this approach provide necessary insight and information to farmers, producers, operators, and equipment manufacturers and dealers to appreciate the performance variations of various scenarios and arrive at logically sound decisions.

4. Conclusions

Various infield bale aggregation scenarios were evaluated and ranked through a computer simulation program developed using a geometrical bale layout and cumulative Euclidean distances principle. An ideal baler operation resulted in a "diamond pattern", while ≥10% variation produces a "random pattern" of bales. All scenarios involving additional equipment with a bale loader were more efficient than the basic single-bale loader aggregation. In general, aggregation efficiency increased as the number of bales handled per trip increased, and the savings were not significant after 12 bales/trip. Field shape, swath width, biomass yield, and bale layout randomness did not affect the aggregation performance. Results are applicable to any field size, as the transporting efficiency increased only marginally with increase in field size (8–260 ha). On collection paths, the MDP method is 4%–16% more efficient than the BP method. The most efficient strategy to collect bales is the application of the self-loading bale picker, followed by parallel run of loader and truck, diagonal grouping, and bale accumulator, and the least efficient is central grouping. Practical recommendations such as a single-bale loader with triple bale handling with MDP produce efficiencies >64%; while a single-bale loader with a parallel run truck handling three and six bales with MDP produce efficiencies >60% and >75%, respectively; and a six bale self-loading picker with MDP produces efficiencies >80% with reference to a single-bale loader "control". Total cumulative distance results of this study are direct functions of time of operation, and fuel consumed, hence they have direct influence on economics of these operations. Further studies are needed to establish their exact relationships.

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Acknowledgments

Technical insight and assistance provided by Mr. Cal Thorson, Technical Information Specialist, NGPRL and the assistance by Ms. Jackie Buckley, Extension Agent, Agriculture and Natural Resources, NDSU Extension Services for arranging interviews with farmers are highly appreciated.

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