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Forest yield maps from GNSS enabled harvester StanForD files: preliminary concepts

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Forest yield map from GNSS enabled harvester StanForD files: preliminary concepts

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Abstract

Background: The stand productivity of fast-growing forest plantation varies across short distances depending on site and forest characteristics. This indicates that forest management would benefit from a site-specific approach. A tool to characterize such productivity variations are yield maps and a cost effective source of data is automatically collected by harvesters. To create such maps we need to understand the effect of geospatial accuracy of tree location recorded by the harvester.

Methods: This study investigated data sets from four stands: two had very accurate tree location, and two were harvester data files that have inaccuracy associated with both the GNSS recording under forest canopy and the physical dislocation of the GNSS. The GNSS unit is on the cabin of the machine, but the tree is felled using a boom and could be up to 12 meters from the cabin.

Results: We establish a spatial resolution for studying variations in stand productivty mean tree volume and stocking across stands to allow the development of forest yield maps from harvester data.

Conclusions: Assessing variability across a range of cell sizes from 10 x10 m to 100 x 100 m, we conclude that a cell size between 30 and 40 m is suitable to use as a reference for calculating volume per hectare and mean stem volume, and 60 m cell is more suitable for evaluating stocking. The variability pattern is consistent for the various accuracy levels. When the trees' position is relatively inaccurate, using mean tree volume and stocking per cell might be a method for mapping productivity from harvester data

Key words: harvester data, forest yield map, Eucalyptus, Uruguay

Background

The length of rotation of fast-growing *Eucalyptus* ssp. plantations in many South America has been reduced due to intensive breeding programs and improvements in silvicultural practices. Brazil and Uruguay are two examples with rotation ages of 6-8 years and 9-12 years respectively for pulpwood plantations (Andreoni and Bussoni 2014; Gonçalves et al. 2013). This type of forest management is intensive in the use of agrochemicals (fertilizers, herbicides) and operations (agrochemical applications, soil preparation) in the establishment phase. Similarly to agricultural crops, forest productivity varies across short distances depending on both site (soil properties and topography) and forest (genotype, stocking, silvicultural practices) characteristics.

Within stand variability (i.e. over short distances) have been quantified based on intensive sampling. Using Site Index (SI) as productivity potential evaluator, Ortiz et al. (2006) mapped and related the variability of productivity with soil and relief of a 6.3 ha stand of *E. grandis* clones in Sao Paulo, Brazil. They assessed the stand based on 41 sample plots and found a significant correlation of productivity with six soil properties and altitude. Barbosa et al. (2012) established and mapped a significant effect of soil pH in the productivity of *Pinus caribaea var. hondurensis* across a 3 ha stand using a grid of 121 points in the state of Mato Grosso do Sul, Brazil. A 3.6 ha surveyed stand of *Pinus taeda* located in Auburn Alabama US were divided in four management zones based on the variation in stocking and productivity across the stand (Brodbeck et al. 2007). These results indicate that forest management would benefit from a site-specific management approach to make the process more efficient with reduction in costs and reduction of environmental impact.

The concept of site-specific management aims to acknowledge the site variability and adjust the silvicultural practices to it instead of managing stands based on average stand characteristics, which is the prevalent approach for forest plantations management. Several other researchers using different study techniques to assess the site variability have proven, or at least pointed out, the viability of the site-specific management approach (du Toit et al. 2010; Gonçalves et al. 2012; González Barrios et al. 2015; Vergara 2004). The adoption of site-specific management has some limitations. For example, the assessment of variations of soil properties and forest variables through intensive sampling would be prohibitively expensive for large areas. In addition, forest managers would expect to see a clear benefit before considering implanting the additional complexity this approach supposes.

In the context of site-specific management, forest productivity maps are a useful resource to quantify and qualify the variations across forested areas. Several techniques were used to develop forest yield maps based on plot samples (Mello et al. 2005; Mello et al. 2009; Ortega et al. 2002), a combination of plots and Light Detention and Ranging (LiDAR) (Chen and Zhu 2012; Rombouts et al. 2010), and trees survey (Brodbeck et al. 2007). A promising and cost effective source of data for mapping productivity is data automatically collected by harvesters when the trees are felled and processed. This topic has been discussed and its benefits explored for forestry plantations (Taylor et al. 2006), however, is yet to be developed.

Productivity maps based on harvester data are used in agriculture. The concept behind the usefulness of yield maps is to evaluate the variation in productivity across the area based on its real harvested production. Having this information at hand provides practitioners with useful information to manage sites specifically according to its characteristics (topography, soil water potentially available, fertility, etc.) and potential, improving profitability and reducing environmental impact through a more targeted application of fertilizers and or pesticides. The required equipment for collecting data for mapping productivity is a harvester equipped with a yield sensor (mass flow or volumetric method) and a GNSS, preferably with differential correction system to improve accuracy. (Bongiovanni and Lowenberg-DeBoer 2006; Griffin 2010; Zhang et al. 2002).

Similar to agriculture harvesters, modern forest harvesters are equipped with a standard system to automatically record data during the operation called StanForD. Developed in Scandinavia in 1988, StanForD is now used in many countries (Skogforsk 2014), becoming a de facto standard. Harvesters than comply with the standard have been widely adopted in harvesting operations in Uruguay, Brazil and Chile. In Uruguay, although there is no official data available, it is estimated that over 60% of the 10 million cubic meters harvested each year (MGAP. DGF 2015) use harvesters. Hence, there is a real potential of using this source of data collection in these countries. When operating with StanForD, there are more than 20 types of files that record data from the operation and the forest, including pri (production individual files) and stm (individual stem data) (Skogforsk, as cited in Olivera and Visser (2014)). These files can be used by forestry companies and contractors to manage production aspects and have been used in numerous research applications (Olivera et al. 2014). Stem files (.stm), compress data for each individual harvested tree, including: stem identification number, DBH, diameter sections measured at 10 cm intervals along the stem, stem volume, individual log volume and logs classification. Moreover, when harvesters are equipped with a GNSS receiver, geographic coordinates of each tree at felling time are included in the files. Stm files also contain manual input information such as species and site identification.

The data collection output of agriculture harvesters and forest harvesters are different. The results of data collected by agriculture harvesters is given in mass (tons or kg) per unit of area (hectare, acres) (Bragachini et al. 2006; Griffin 2010; Whelan and Taylor 2013). Then the development of yield maps can be achieved by cleaning the data and interpolating productivity values from the original machine records (Lyle et al. 2014; Robinson and Metternicht 2005). Forest harvesters on the other hand do not output units of volume per hectare; they record individual tree data and a spatial location that have two sources of errors:

a) GNSS location, which is typically mounted in the cabin of the machine. The tree is felled by the harvester head, which is mounted at the end of the boom that can be up to 12 m long depending on make and model; thus, the tree is recorded at the location of the cabin of the machine at felling time.

b) GNSS accuracy, which for common grade GNSS in similar conditions (i.e. forest environment with partial sky coverage) averages between 3 to 6 m with standard deviations up to 12 m (Veal et al. 2001; Wing 2008; Wing et al. 2005; Yoshimura and Hasegawa 2003). These errors make accurately evaluating the distribution of volume and stocking per hectare a challenging task.

The overall objective of this study is to improve our understanding of spatial resolution for studying variations in volume and stocking across forested stands, and establish guidance for actual spatial resolution that would allow the development of fit-for-purpose forest yield maps from harvester data.

Methods

Study sites

To improve our understanding of spatial resolution to develop productivity maps from harvester data, four sets of data comprising trees' individual information are analysed. Two stands (1 and 2) have very accurate tree position and two stands (3 and 4) have a much lower level of geospatial accuracy with the use data automatically collected by a harvester.

Stand 1 is a surveyed stand located 9.6 km north of Auburn Alabama in the United States. Each tree's position within the stand was measured with sub-centimetre accuracy as described in Brodbeck et al. (2007). The information contained in this dataset was tree identity; X, Y and Z coordinates; and diameter at breast height (DBH). With this information we calculated for each tree height and volume using the same equations for pulpwood described by Brodbeck et al. (2007) shown as equations 1 and 2 respectively. For both equations, DBH is in cm.

$$\textit{Height (m)} = 12.689 + 0.253 * \text{DBH} \quad (1)$$

$$\textit{Volume } (m^3) = 0.23233 * \text{DBH}^2 * \text{height} \quad (2)$$

Stand 2 was artificially created in ArcGIS 10.2.2 using the same boundary of stand 3. Initial tree spacing was uniform with 3.5 m between rows and 2.15 m between trees in the same row, resulting in a theoretical stocking of 1328 trees ha^{-1}. This was randomly reduced by 27% to 967 trees ha^{-1} to simulate a typical level of mortality. In addition, to create a level of in-stand variation individual tree volume was increased in the direction northeast to southwest, to deliberately create a spatial variation trend.

Stem records for stands 3 and 4 were obtained from .stm files from a single-grip harvester equipped with a combined GSM-GNSS antenna fitted on the cabin for geospatial data collection and communication. The control system is Opti4G 4.715, which complies with the StanForD standard. These two stands are both even-aged, first rotation *Eucalyptus* ssp. forest plantations located in the northern part of the Rio Negro department in Uruguay. All harvested trees are debarked and cross-cut for pulpwood logs.

The difference between surveyed stand data and harvester data can be readily seen in Figure 1. Stands 1 and 2 clearly show the trees in planted rows. Stands 3 and 4, in addition to the two sources of location error, also show the path of the harvester as the trees are felled. Table 1 presents more information of the stands. The analysis variables are volume per hectare in m^3, stocking (trees ha^{-1}) and mean tree volume. The stands that have accurate trees position serve as models for the analysis of a suitable spatial resolution to study these three variables. Further studies based on harvester data then apply the concepts.

Figure 1

Table 1

Cell size analysis

Using the trees' position, a map showing productivity variation can be generated directly by dividing the area in equal size cells and adding the volume of all trees within each cell. To determine a suitable cell size for productivity mapping, a cell size analysis was carried out dividing each stand in square cells of increasing size: 10 m, 20 m, 30 m, 40m, 60 m and 100 m (Fig. 2). This analysis was done in two steps; first using the tool point to raster in ArcGis 10.2.2 (Esri Inc., 2014), which converts a point vector layer (stem records) into a raster layer giving the value of a single variable to each cell; this step was repeated for each combination of variable (3) cell size (6) and stand (4) (72 times). This information was then analysed in an Excel spreadsheet and for each stand and cell size the variability of the three variables were studied. This analysis assesses how the coefficient of variation (CV) of each variable changes as the cell size increases within the stand. As the cell size increases, the CV is expected to decrease until it reaches the size and the overall average of the stand. It is expected that the CV stabilizes and then indicate that the variability due to a cell size is small and the remaining variability is of the stand itself.

Figure 2

Results and discussion

Cell size distribution

Volume per hectare and stocking per hectare are calculated only from cells that are completely within the stand boundaries (Fig. 2). This is because these variables are related to the total cell area and expressed per hectare. For calculating mean stem volume from 20 to 100 m cell all cells comprising 30 or more stem records are used, even though they can fall partially outside the stand. Table 2 summarizes the number of cells included from each stand for each variable. As the cell size increases the proportion of useable cells for calculating volume and stocking decreases because of the increasing number of cells that fall partially outside of the stand (Fig. 2). Conversely, the proportion of useable cells for calculating mean stem volume stays stable for all cell sizes.

Table 2

At 10 m cell size there are a large number of empty cells in stands 3 and 4. This clearly does not represent the reality because the area is a plantation forest and there should be very few, if any empty cells. For these two stands, there are also 20 m empty cells. At the 60 and 100 m cell size on the other hand, the results are similar to the overall average of the whole stand and the number of cells that fall completely inside the stand decreases to a point that only one 100 m cells fall completely inside stand 1 (Fig. 2).

Volume per hectare

The increment in cell size only slightly affects the averages, maintaining its value within ± 10% in the majority of cases (22 out of 24) (Tabs. 1 and 3). However, as the cell size increases the CV of volume per hectare decreases consistently for all stands independently of the kind of records they are (Fig. 3). The range of the CV as the cell size changes is different for the different stand types. Both stands that have accurate tree location (stands 1 and 2) have a lower CV at 10 m cell size (32 – 33%) than the harvester data stands (67 – 77%). The CV decreases rapidly as the cell size augment to 20 m for all stands. The values of CV continue decreasing at similar rate for 30 m cell in stand 3 and 4, whereas for Stands 1 and 2 the decrease asymptotes. Between 30 m and 60 m cell size, the CV decreases steadily in all stands. The pattern of variation suggests that the variability due to cell size contributes more to the overall variability at 10 m to 20 m cell. Whereas, between 30 m to 60 m cell size the variability can be attributed to other causes from the environment or the forest such as soil characteristics, topography, stocking and even tree location accuracy for stands 3 and 4. At 60 m cell however, the number of cells that fit in a small stand –Stand 1 for example– is reduced, resulting in a coarse resolution for further analysis of volume. For 100 m cell, the CV is the lowest for Stands 2 to 4 as the area of each cell represents more the average of the stand and the number of cells are reduced (Tab. 2).

Figure 3

As such, when tree locations are accurately recorded, using a cell size between 30 m and 40 m constitutes a reasonable unit size to subdivide a stand to study the volume variation (productivity) across its area.

Stocking

CV values of stocking for all stands follow a similar pattern as volume; the CV diminishes as cell size increases and the averages are stable for stands 2, 3 and 4, and similar to the overall average (Tabs. 1 and 3, and Fig. 4). For stand 1, all cell sizes overestimate the average stocking between 11 to 20% because the edges of the stand that have the lower stocking (Figs. 1 and 2) are excluded from the analysis as they are not totally within the stand.

Table 3

The variability decreases rapidly from 10 m to 30 m cell for stands 1, 3 and 4, whereas for stand 2 it happens from 10 m to 20 m cell size. For the latter, lower values of CV, ranging from 19 to 1%, across the different cell sizes reflects the evenly distributed stocking across the stand. There is however an effect of cell size at 10 m and even at 20 m for this stand reflected in the higher CV. In the case of stand 1, the CV falls up to the 40m cell and then stabilizes at a value around 21%, showing the real variation in stocking across the stand; variation that is clear in Figures 1 and 2. Stand 3 presents a CV value that decreases as cells size augment up to 60 m, whereas stand 4 stabilizes between 30 m and 60 m.

Figure 4

For stand 1, which has accurate tree location and uneven stocking, the most suitable cell for stocking analysis is 40 m to 60 m as the CV is stable over this range and suggests that the remaining variation (CV of 21%) is independent of cell size. For stand 2, which has homogeneous stocking across the stand and accurate tree location, a cell size of 30 m or higher is suitable. If however the distribution is not known a priori (like harvester data), working with 60 m cell is a suitable option for mapping stocking. Evidence of this is seen in stand 3 where stocking stabilizes at 60 m cell size. Stand 4 CV is stable (20 – 26%) between 30 m and 60 m cell, suggesting that a cell size in this range would be suitable for stocking analysis. The stable pattern for these two stands also shows that at this level of resolution, the errors in GNSS accuracy affecting the variability may be negligible.

Another important factor to consider is the size of the stand (or area evaluated); stands smaller than 4 ha, such as stand 1, would fit a very low number of 60 m cells (Fig. 2 and Tab. 2). This is not desirable if there is a variation in stocking across the stand. Then the use of 40 m cell is advisable.

Mean tree volume

As for volume and stocking, mean tree volume varies considerably at 10 m cell (Fig. 5). This variation decreases dramatically by the 20 m cell size and falls steadily up to 100 m. Even at 100 m, there is variation, which suggests there is an effect from the environment or the forest itself affecting stem mean volume in all four stands. These results suggest a cell size between 20 m and 40 m is suitable for further analysis. At smaller cell size, the high CV and low number of trees per cell would bias any analysis as the cell size affects the variation. Over this range, the cell sizes are too large to capture the variation across the stand due to the large proportion of the stand each cell represents (Tab. 2).

Figure 5

Conclusions

Based on the changes in CV across the studied range of cell sizes, we conclude that a cell size between 30 and 40 m is a suitable cell size to use as reference for calculating volume per hectare (productivity) and mean stem volume to further compare and develop the concepts of forest productivity maps.

For evaluating stocking, the use of 60 m cell is more suitable in situations where the variation in stocking across the area is unknown such us when using harvester data. For stands smaller than 4 ha a 40 m cell might be used to obtain a greater number of points.

The pattern of CV variation is consistent in both type of stands (accurate tree location and harvester data) for all three variables. However, there is still some uncertainty of what proportion of the variation that can be attributed to the environment and the tree location accuracy for stands 3 and 4. However, this study has shown that even if the trees' position is not accurate, using mean tree volume and stocking per cell can be a method for mapping productivity from harvester data. An idealised future study would fully survey all trees in a stand and then capture the corresponding harvester data set. This would allow a more complete understanding of what variation is attributable to the geospatial inaccuracy of the harvester versus the actual variation in the stand.

Competing interests

The authors declare that they have no competing interests

Authors' contributions

AO sourced the harvester data, created the stand 2 data, carried out the analysis and wrote the manuscript. RV conceived the idea for the analysis, sourced the stand 1 data and reviewed the manuscript. Both authors read and approved the final version of the manuscript.

Authors' information

AO is a PhD candidate from Uruguay whose research project is looking at "Exploring some opportunities of the integration of GNSS in harvesters". He has worked for over 10 years in the forest industry in his home country. RV is Associate Professor and the Director of Studies at the Forest Engineering degree at the NZ School of Forestry; he is the senior supervisor of AO in his PhD project.

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Lis of Figures

Figure 1: Maps of the four stands with details of location and tree records pattern. Stand 1 has accurate tree location and uneven stocking, stand 2 has accurate tree location and even stoking, and stands 3 and 4 are plotted from stm files.

Figure 2: Detail of stand 1 divided in six cell sizes as indicated in each map. Values refer to the range of number of trees per cell.

Figure 3: Changes in the range of volume per hectare and its coefficient of variation as cell size increases from 10 m to 100 m for the four stands. No values for 100 m cell in stand 1 because there is only on cell.

Figure 4: Changes in the range of stocking per hectare and its coefficient of variation as cell size increases from 10 m to 100 m for the four stands. No values for 100 m cell in stand 1 because there is only one cell

Figure 5: Changes in the range of mean stem volume and its coefficient of variation as cell size increases from 10 m to 100 m for the four stands.

Tables

Table 1: Characteristics of the four studied stands.

	Stand 1	Stand 2	Stand 3	Stand 4
Location	Auburn AL - US	--	Rio Negro - Uruguay	Rio Negro - Uruguay
Species	*Pinus taeda* (L.)	--	*Eucalyptus dunnii* (Maiden)	*Eucalyptus maidenii* (F. Muell)
Age (years)	25	--	19	19
Year of data collection	--	--	2014	2014
Area (ha)	3.6	6.65	6.65	8.05
Average stocking (trees ha^{-1})	661	967	967	899
Thinned	at age 16	no	no	no
Volume studied	Total volume	Commercial volume	Commercial volume	Commercial volume
Average volume m^3ha^{-1}	157	506	464	213
Mean stem volume (m^3)	0.24	0.52	0.48	0.24

Note: Commercial volume refers to volume of commercial logs only.

Table 2: Detail of cell divisions for the four stands and six cell sizes.

	Cell size (m)	10	20	30	40	60	100
Stand 1	Number of cells	359	103	52	29	15	6
	Number of cells - no edges	311	67	27	13	3	1
	Number of empty cells	1	0	0	0	0	0
	Cells used for mean volume calculation	311	63	34	24	15	6
Stand 2	Number of cells	699	188	88	53	23	11
	Number of cells - no edges	621	146	58	32	11	3
	Number of empty cells	0	0	0	0	0	0
	Cells used for mean volume calculation	621	161	76	47	22	11
Stand 3	Number of cells	562	174	83	51	22	9
	Number of cells - no edges	551	166	61	29	13	4
	Number of empty cells	72	2	0	0	0	0
	Cells used for mean volume calculation	562	166	75	47	22	9
Stand 4	Number of cells	791	241	122	75	36	15
	Number of cells - no edges	791	207	71	33	14	4
	Number of empty cells	93	2	0	0	0	0
	Cells used for mean volume calculation	791	207	95	59	33	13

Table 3: Average values of the three variables for each stand and each cell size.

	Cell size (m)	10	20	30	40	60	100
Stand 1	Volume per hectare (m^3)	168	169	167	168	170	--
	Stocking (stems ha^{-1})	733	760	770	793	792	--
	Mean stem volume (m^3)	0.26	0.25	0.25	0.25	0.26	0.26
Stand 2	Volume per hectare (m3)	507	513	512	509	523	531
	Stocking (stems ha^{-1})	968	966	968	966	961	957
	Mean stem volume (m^3)	0.52	0.53	0.53	0.52	0.52	0.51
Stand 3	Volume per hectare (m3)	556	459	462	450	455	451
	Stocking (stems ha^{-1})	1162	981	974	952	977	1006
	Mean stem volume (m^3)	0.50	0.48	0.48	0.48	0.47	0.45
Stand 4	Volume per hectare (m3)	217	200	196	193	184	203
	Stocking	914	842	826	809	778	850
	Mean stem volume (m3)	0.24	0.24	0.24	0.24	0.23	0.24

Figure

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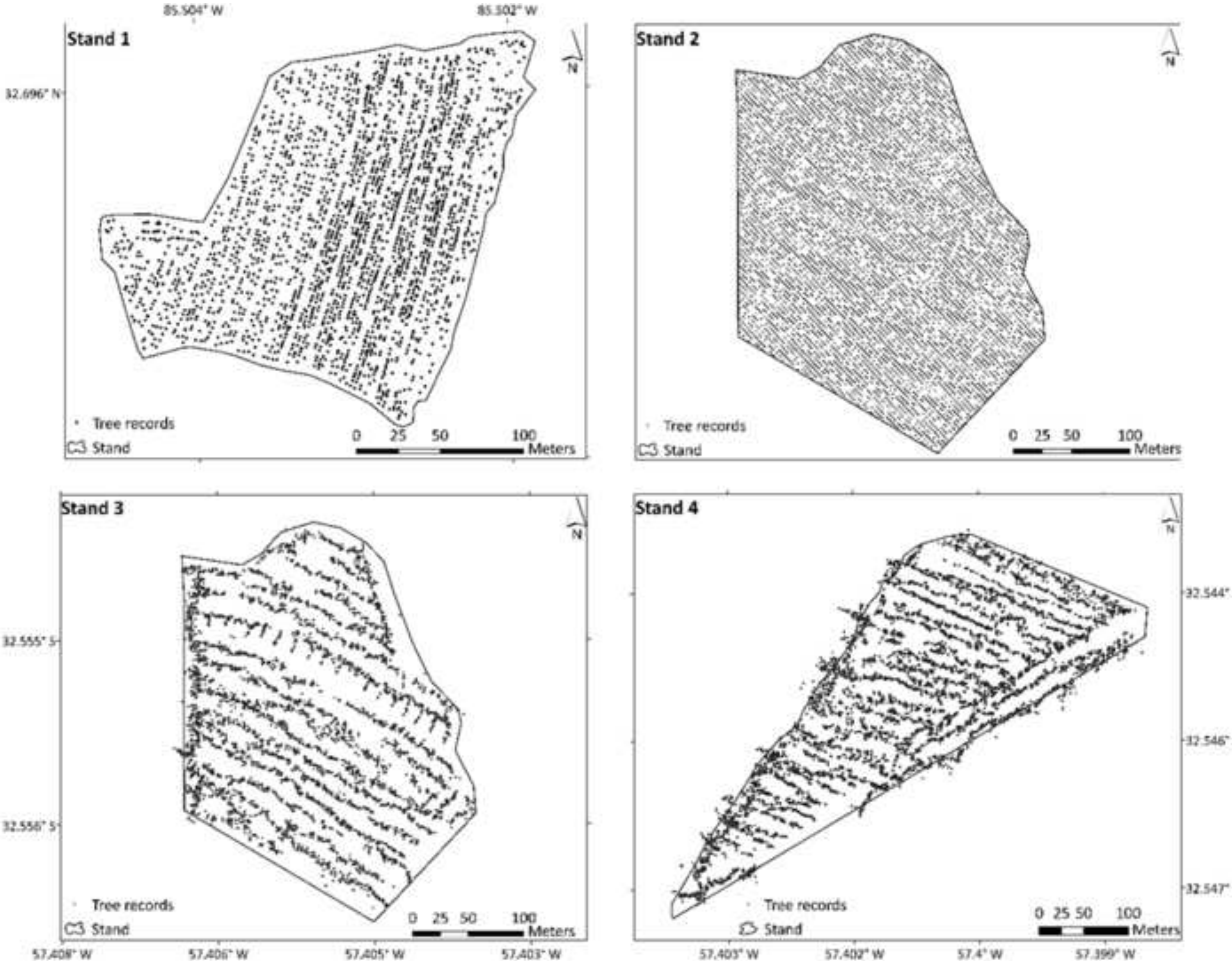

Figure

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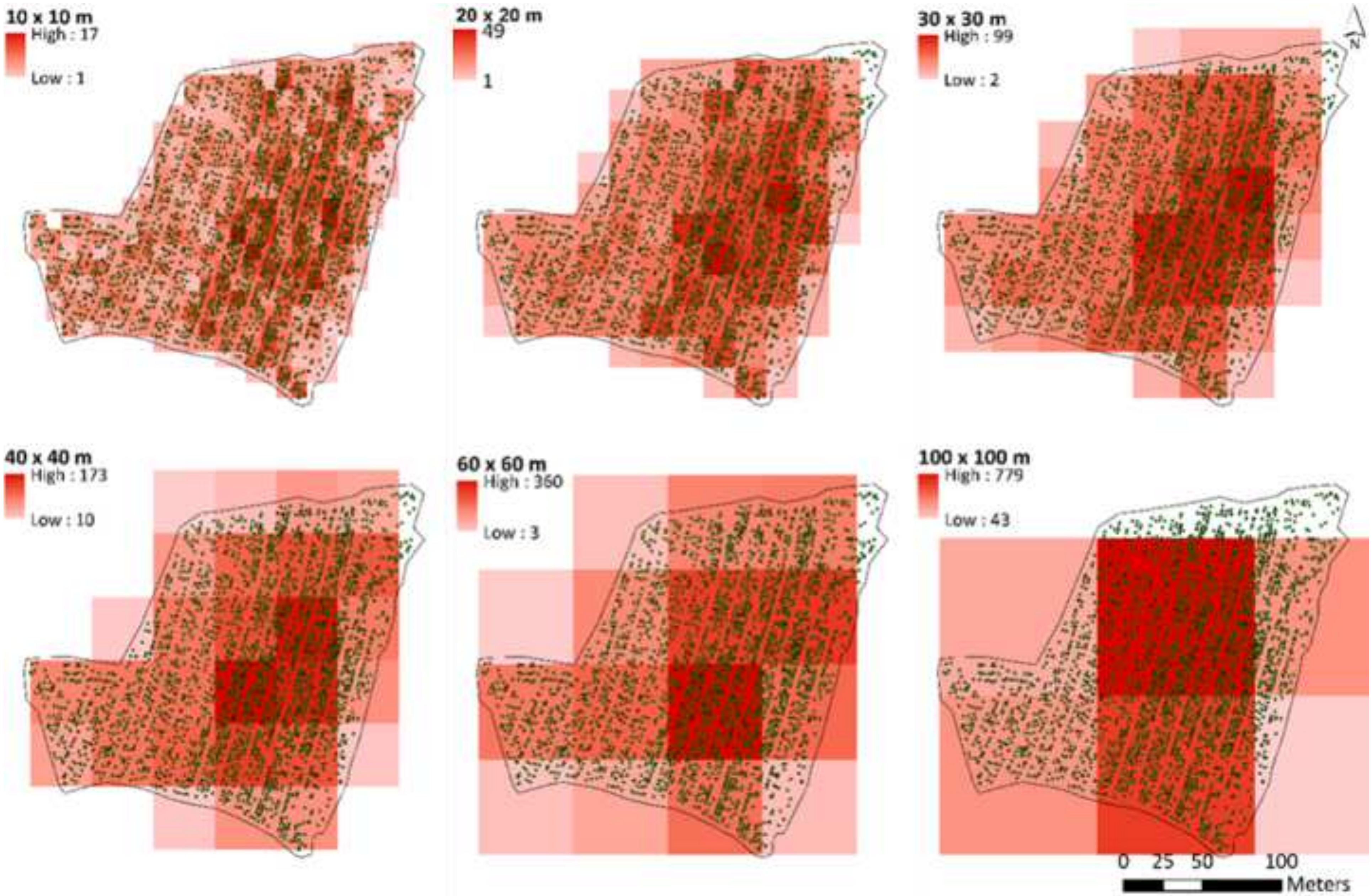

Figure

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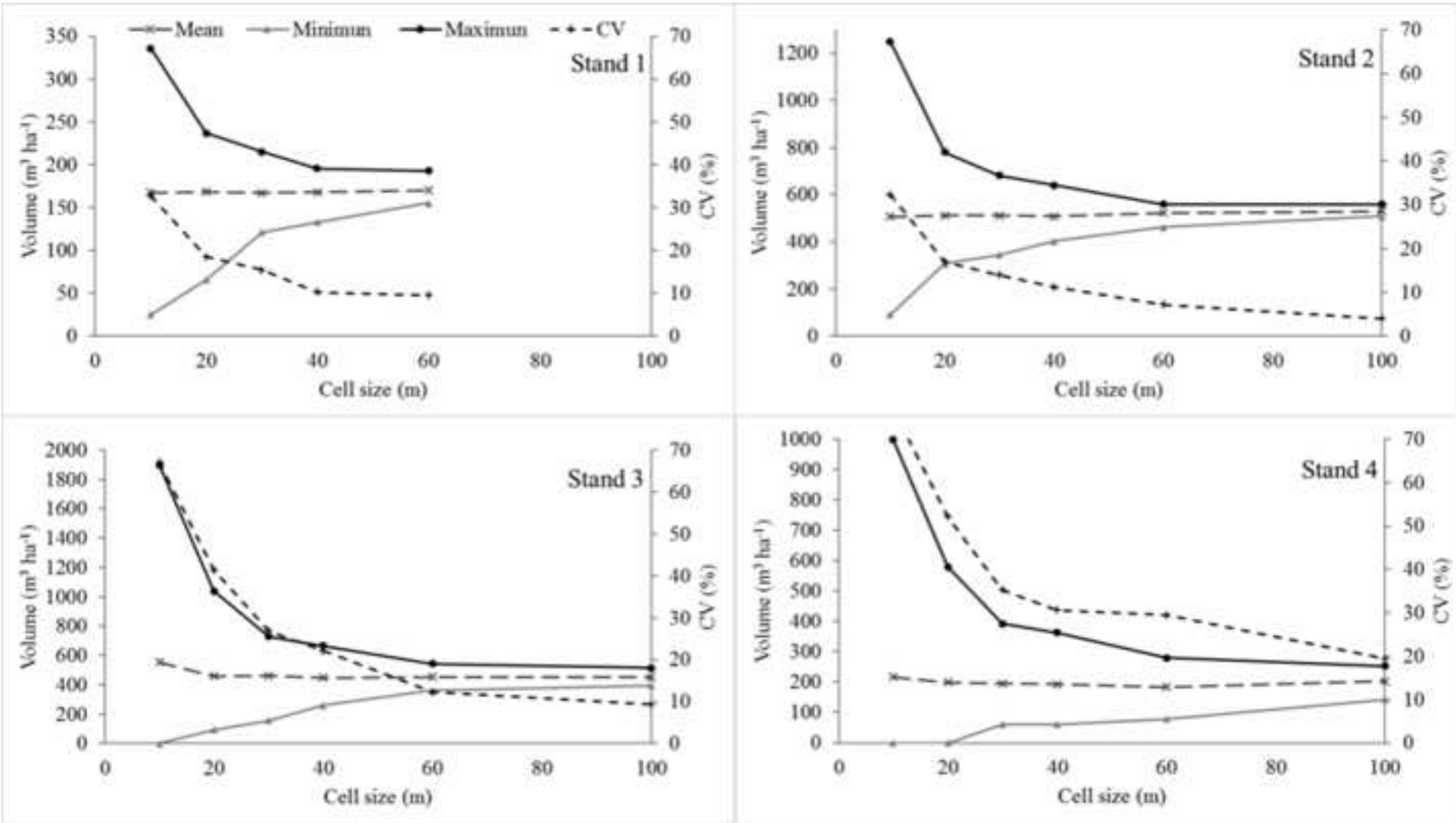

Figure

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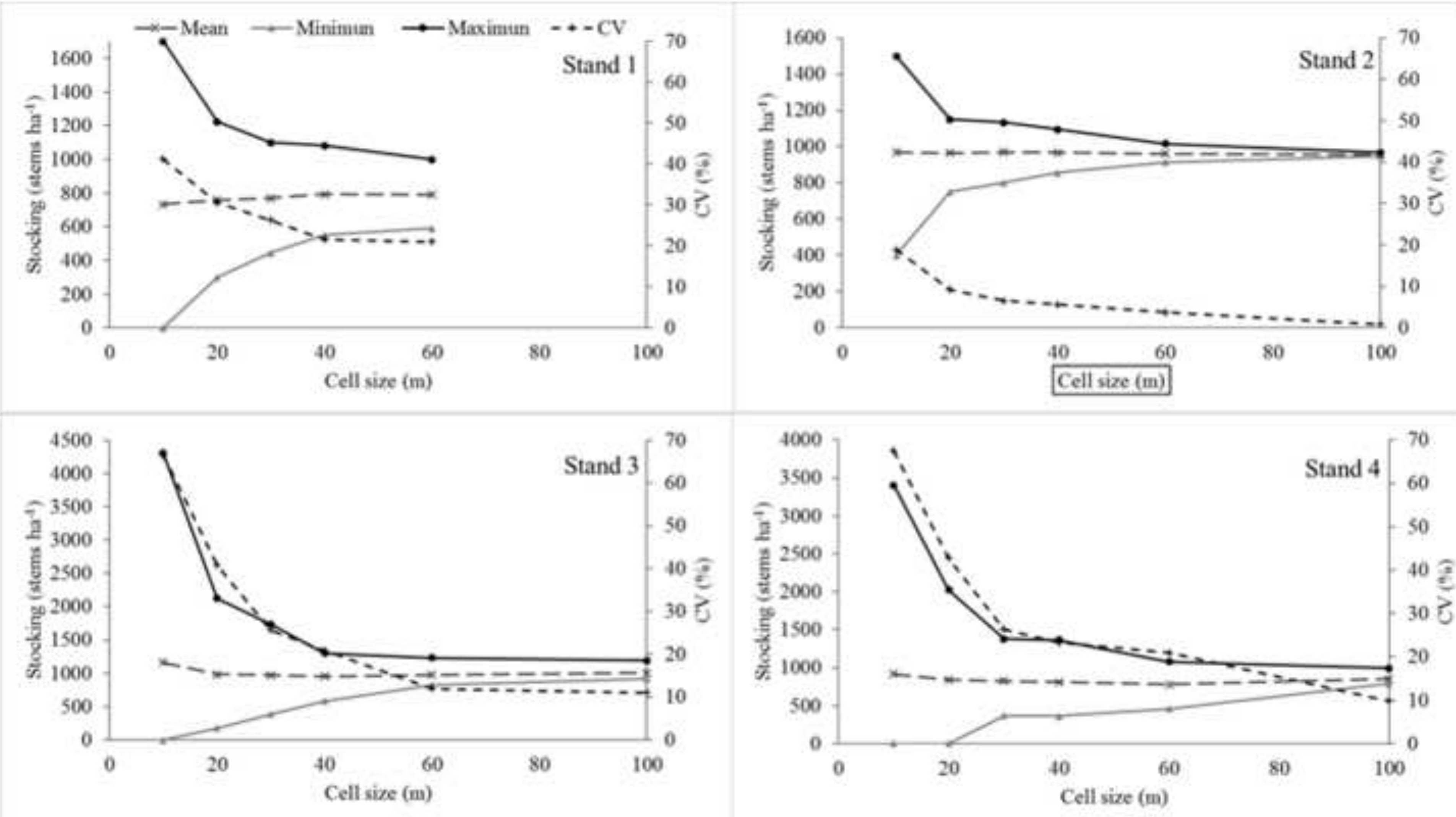

Figure

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