PROBABILISTIC ESTIMATES OF COSTS FOR TREATING SOUTHERN PINE BEETLE INFESTATIONS BY CUT-AND-LEAVE SUPPRESSION MEASURES DURING AN OUTBREAK

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ABSTRACT

The Bienville National Forest (BNF) in central Mississippi was affected by a southern pine beetle (SPB; *Dendroctonus frontalis* Zimmermann) outbreak between 2015 and 2019. In 2017, cut-and-leave treatments were applied to many of the actively enlarging infestations within the forest in an attempt to mitigate the spread and damages due to SPB. Contractors treated 330 different spots on the BNF (out of a total of 1,660 recorded SPB spots, or approximately 20 percent of all spots), at an average cost of $645 per acre. The spot and cost data were obtained in an effort to provide a probabilistic assessment of cut-and-leave treatment costs for the forest. A two-parameter Weibull distribution was ultimately selected to model the probabilities of observing a particular spot size. The spot size-density probabilities from 2017 can be combined with an estimate of the likely total number of SPB infestation spots, and an estimate of per unit (e.g., acre) treatment costs, to estimate the total treatment cost for a particular region within a desired length of time. This information could be used to inform cost estimates for planning and mitigation efforts for future outbreaks on this or comparable forests.

INTRODUCTION

The southern pine beetle (SPB), (*Dendroctonus frontalis* Zimmermann), is the most destructive insect pest of pine in the Southern United States (Duerr and Mistretta 2013). Pye and others (2011) state SPB outbreaks occurred, on average, every 5 to 10 years from 1977 to 2004, while others report slightly shorter intervals of every 5 to 7 years beginning in the 1960s up to the 1990s (Asaro and others 2017, Clarke and Nowak 2009). The last widespread outbreak occurred in the late 1990's and early 2000's (e.g, Oswalt and others 2016). These beetles are short-legged, stout, and about one-eighth inch long (Frank and others 2019) and occur in a generally continuous distribution across the Southern and Southeastern United States, roughly coinciding with the distribution of loblolly pine (*Pinus taeda* L). Its range extends from New Jersey to Florida to Texas to Illinois (Clarke and Nowak 2009). Southern yellow pines are the primary hosts of SPB (Duerr and Mistretta 2013). Shortleaf (*Pinus enchinata* Mill.), loblolly, Virginia (*Pinus virginiana* Mill.), and pitch (*Pinus rigida* Mill.) pines appear to be the preferred hosts. SPB usually attack trees that are at least 15 years old. The SPB must kill its host pines to reproduce, and attacks trees *en masse*.

Pye and others (2011) reported short-run impacts to timber producers around $1.2 billion, or about $43 million per year from the 1980s to 2010. While SPB geographic "hotspots" are found annually in local areas and woodsheds, the last widespread outbreak in the late 1990's and early 2000's (e.g., Oswalt and others 2016) resulted in an estimated $1.5 billion dollars of economic damage (Clarke and Nowak 2009, Duerr and Mistretta 2013). The volume of timber killed annually by SPB from 1973 through 2004 ranged from 3 to 417 million cubic feet (Pye and others 2011). They show there have been eight outbreaks of varying intensity from 1973 to 2003, each geographically spanning only portions of the region.

Mississippi has a comprehensive program for SPB prevention (Kushla and others 2019) that includes educational efforts and thinning cost shares. Kushla and others (2019) essentially estimated that this SPB outbreak prevention program can have around a $5.5 to 12.0-million-dollar impact annually on the economy. This program is in conjunction with the Southern Pine Beetle Prevention Program (SPBPP) (a joint

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Citation for proceedings: Willis, John L.; Self, Andrew B.; Siegert, Courtney M., eds. 2022. Proceedings of the 21st Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SRS-268. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 262 p. https://doi.org/10.2737/SRS-GTR-268.

effort of the Forest Service, U.S. Department of Agriculture and Southern Group of State Foresters) that is designed to encourage and provide cost-share assistance for silvicultural treatments to reduce stand and forest susceptibility to SPB.

Studies have actually proposed insuring forests to protect against loss due to SPB (Chen and others 2019). Pye and others (2011) state that southern pine forests periodically experience large SPB outbreaks somewhere in the region on relatively short cycles. Although damages southwide have not been found to exceed 8 percent of typical sawtimber or pulpwood harvests in any given year, the concentration of mortality to subregions suggests that impacts to local timber markets would be more severe. This could be true most especially for those markets containing a relatively larger amount of Forest Service national forest land (e.g., Carter and others 1991). Mississippi has had relatively minor outbreaks compared to other States, with the largest one occurring in the late 1970's and early 1980's (Pye and others 2011). Relatively smaller acreages compared to other States were infested during the last regionwide outbreak occurring in the late 1990's and early 2000's.

When beetle populations are low (endemic), attacks are generally restricted to senescent, stressed or damaged pines; however, epidemics periodically occur (Thatcher and others 1980). During epidemics, SPB infestations often begin in weakened or injured trees, but the high beetle populations can invade and overcome healthy vigorous trees by attacking in large numbers over a short period of time (Thatcher and others 1980). Widespread and severe tree mortality can occur during epidemics, SPB spots (groups of infested trees) may expand at rates up to 50 feet per day, and uncontrolled infestations may grow to thousands of acres in size (Billings 2011). SPB attacks subsequently encourage attack by other insects, including Ips bark beetles (Clarke and Hartshorn 2021) and eastern subterranean termites (Little and others 2012).

Over the last 15 to 20 years (1996–2016), major SPB outbreaks spanning more than a county/parish or two and persisting for longer than a year have largely failed to materialize across most of the Piedmont and Coastal Plain regions, where intensive pine plantation culture is most common. This has occurred despite that from the 1950s through the present day, a 20-fold increase in pine plantation area has been observed across this region (Asaro and others 2017). They believe substantial changes to the management and condition of the southern pine resource in the form of plantations that are genetically improved, younger, faster growing, less overstocked, and more fragmented is a robust explanation for regional declines in SPB outbreak activity. However, the Bienville National Forest (BNF) in central Mississippi was affected by a SPB outbreak between 2015 and 2019. Thus, as evidenced by this outbreak, SPB attacks still do occur and we as natural resource managers should expect them to occur.

In a disturbance event, response is often important to prevent further damage and impacts in a forest. In events like SPB outbreaks, resource planning for treatment and mitigation are vital to prevent additional and undesirable losses. In 2017, cut-and-leave treatments were applied to many actively enlarging infestations within the BNF that posed an imminent threat to active red-cockaded woodpecker (*Dryobates borealis*) clusters, and neighboring and susceptible private property, in an attempt to mitigate the spread of and losses due to SPB. Contractors treated 330 different spots on the BNF (out of a total of 1,660 recorded SPB spots, or approximately 20 percent of all spots), at an average cost of $645 per acre. The treated locations on the BNF during 2017 provide prior information to leverage into a means of estimating infestation spot sizes and associated costs with future outbreaks. The majority of the treated locations are smaller in acreage, and thus skew the distribution towards smaller areas. To develop a means of estimating the likelihood of areas to be treated, the spot size and number, and the associated treatment cost, data was obtained in an effort to provide a probabilistic assessment of cut-and-leave treatment costs for the forest, this will be accomplished by testing various probability distributions and eventually employing a particular probability distribution.

METHODS

Weibull Distribution

The Weibull distribution is widely used in forestry and natural resources applications (Cao 2004, Evans and others 2019, VanderSchaaf 2015) as it is effective in the characterization of a variety of distributions of a variable of interest, in this case, SPB cut-and-leave treatment areas, or spot size. The distribution can be found by:

$$f(x)=\left(\frac{c}{b}\right)\left(\frac{x-a}{b}\right)^{c-1}exp\left[-\left(\frac{x-a}{b}\right)^{c}\right] \quad (1)$$

where

x is the SPB cut-and-leave treatment area spot size (in acres) and the parameters for location (a) represents the minimum value, and scale (b) and shape (c) are often estimated using maximum likelihood estimators (MLE). The per acre cost is applied to this value to estimate the probability of treatment costs. When the location parameter (a) is set to 0 the three-parameter Weibull distribution reduces to the two-parameter Weibull distribution.

For this study, several initial attempts were conducted to fit the three-parameter Weibull distribution using maximum likelihood estimation (MLE) of the observed spot size (acres)-density relationship shown in figure 1. A variety of software was used. Additionally, the exponential distribution and

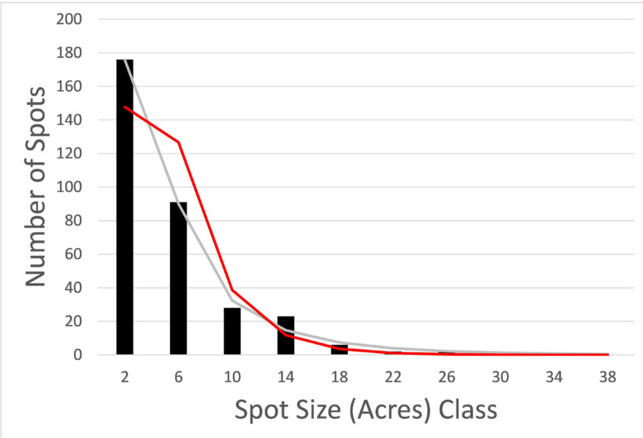


Figure 1—Observed number of southern pine beetle (SPB) cut-and-leave treated spots by size-class in acres, the two-parameter Weibull probability distribution function (PDF) as estimated using Solver in Microsoft Excel (gray curve), and a maximum likelihood estimation (MLE) exponential PDF (red curve).

a PERT-based beta distribution approach were examined. However, results were unsatisfactory, largely underpredicting the number of smaller spot sizes (acres), the exponential probability distribution function (PDF) is depicted in figure 1. Parameter estimation attempts were made by both separating the number of spots by size class (acres) into individual observations (e.g., 330 observations—hence n = 330) as well as just using the total number of spots within each of the 9 (hence n = 9) observed size (acres) classes (e.g., 2, 6, 10, 14, 18, 22, 26, 30, and 34) (fig. 1).

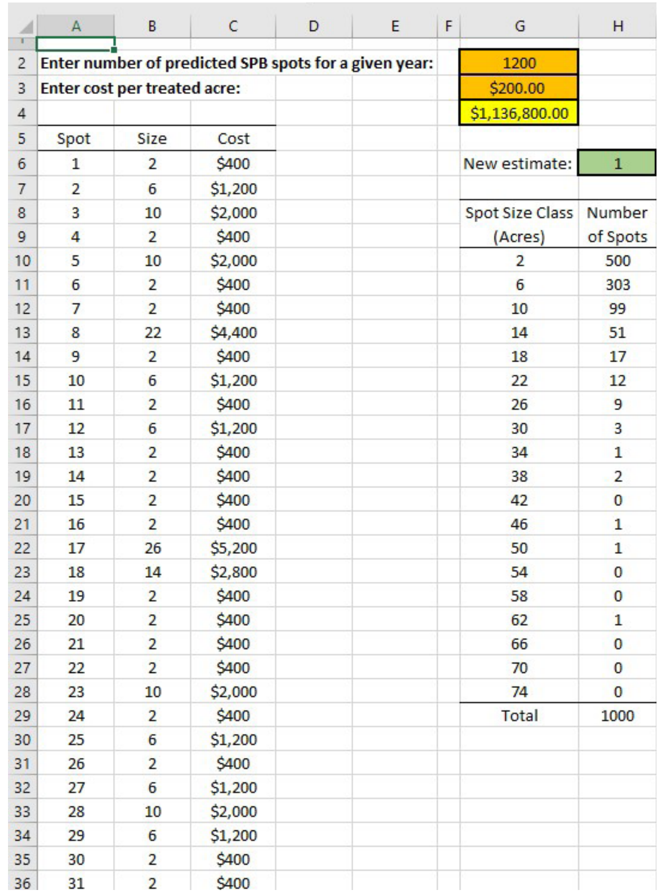
Thus, due to the unsatisfactory results, after initially setting the location (a) parameter to 0, the two parameter Weibull distribution was fit by using the Solver application within Microsoft Excel (2013). The scale (b) and shape (c) parameters were estimated by minimizing the sum of square errors (SSE) from the observed and predicted number of spots by area (acres) class. Similar concepts of estimating Weibull parameters by minimizing SSEs were described by Cao (2004), Cao and McCarty (2006), and Evans and others (2019), what Evans and others (2019) described as linear estimators. Parameter estimates for the Solver estimated two-parameter Weibull distribution and the exponential MLE estimates are shown in table 1 along with their associated SSEs.

Table 1—Parameter estimates of the two-parameter Weibull probability distribution function (PDF) using the Solver application within Microsoft Excel and maximum likelihood estimates (MLE) of the exponential PDF

PDF	n	Location	Scale (b)	Shape (c)	SSE
Weibull	9	–	2.959727	0.697766	95.56
Exponential	330	1.989795	3.367781	–	2,318.12

SSE = sum of square errors.

Sample sizes differ because parameters were estimated both following grouping spot sizes (acres) into groups (e.g., binning) and as separate observations.



	A	B	C	D	E	F	G	H
1								
2	Enter number of predicted SPB spots for a given year:						1200	
3	Enter cost per treated acre:						$200.00	
4							$1,136,800.00	
5	Spot	Size	Cost					
6	1	2	$400				New estimate:	1
7	2	6	$1,200					
8	3	10	$2,000				Spot Size Class	Number
9	4	2	$400				(Acres)	of Spots
10	5	10	$2,000				2	500
11	6	2	$400				6	303
12	7	2	$400				10	99
13	8	22	$4,400				14	51
14	9	2	$400				18	17
15	10	6	$1,200				22	12
16	11	2	$400				26	9
17	12	6	$1,200				30	3
18	13	2	$400				34	1
19	14	2	$400				38	2
20	15	2	$400				42	0
21	16	2	$400				46	1
22	17	26	$5,200				50	1
23	18	14	$2,800				54	0
24	19	2	$400				58	0
25	20	2	$400				62	1
26	21	2	$400				66	0
27	22	2	$400				70	0
28	23	10	$2,000				74	0
29	24	2	$400				Total	1000
30	25	6	$1,200					
31	26	2	$400					
32	27	6	$1,200					
33	28	10	$2,000					
34	29	6	$1,200					
35	30	2	$400					
36	31	2	$400					

Figure 2—Partial screenshot of the spreadsheet application developed using the two-parameter Weibull distribution to estimate southern pine beetle (SPB) cut-and-leave control costs for a particular region over time, in this example for a period of 1 year. Individual spot-size (acres) predictions (Columns A and B) are binned into the summary spot size (acres) classes found in cells G8:H29.

RESULTS AND DISCUSSION

The Solver estimated two-parameter Weibull distribution produced a much more meaningful and useful depiction of the likely number of treated SPB infestations by spot size (acres), including a substantial reduction in SSE as compared to the other parameter estimation techniques for the exponential (table 1) and Weibull distributions.

An Excel-based application was developed using the two-parameter Weibull distribution to estimate SPB cut-and-leave control costs for a particular region and length of time, for example, 1 year (fig. 2). Users can use the default parameter estimates presented here in table 1 or can manually change them to represent any likely amount of SPB infestations requiring cut-and-leave suppression measures by treatment acre size-class. For example, the Weibull PDF depicted in figure 1 can be modified to produce a more representative probability of treatment spot size-density distributions for a particular region and time.

Users then can enter the number of likely total SPB infestations (or spots) requiring cut-and-leave treatment for a particular length of time (e.g., 1,660 spots annually for the BNF in 2017) and the SPB control costs per acre. The application then provides 25 estimates of the likely total treatment costs across the particular region and length of time depending on the user-specified number of likely spots requiring treatment, the estimated SPB control costs per acre, and the Weibull PDF of the likely relative amounts of SPB spot sizes (acres). The application then calculates the average estimated control costs for the region and length of time across the 25 estimates and determines the minimum and maximum estimated costs. These upper and lower cost estimates provide the user some idea of the potential range in total SPB treatment costs for cut-and-leave suppression measures.

Variability in the total cut-and-leave treatment costs is produced through the use of list sampling. List sampling involves using some type of randomization process to select observations given the probability of their occurrence (Husch and others 2003). As seen in table 2, given the estimates of the scale (*b*) and shape (*c*) parameters presented in table 1, the probabilities of cut-and-leave treatment spot sizes (acres) can be determined. A convenient finding provided by the Weibull distribution itself is that for the scale parameter (*b*). This value approximates the 63rd percentile for the response variable (Bailey and Dell 1973). The approximate spot size located at the 63rd percentile from this study was found to be 2.96 acres (table 2).

Note, there is a greater probability of a treated spot size being 2 acres than 22 or 34 acres in size. To randomly assign a spot size (acres) to a particular spot given the probabilities in table 2, a random number between 0 and 1 can be generated, and the spot size (acres) assigned will depend on where that random number falls within the cumulative spot size probabilities (CDF) (table 2, fig. 3). Hence, there is a wider interval for assigning a value of 2 acres than 22 acres, and hence there is a greater probability of any random number from 0 to 1 falling within the 2-acre range and thus that acreage being assigned to an SPB spot. There is a 53.27 percent chance of a SPB spot treated by cut-and-leave being 2

Table 2—Number of sampled observed spots by size (acres) of cut-and-leave treatment from the Bienville National Forest (BNF) in 2017

Spot size	Observed spots	CDF	Probability	Spot size acre interval
acres	*number*			
2	176	0.5327	0.5327	213.1
6	91	0.8055	0.2728	322.2
10	28	0.9035	0.0980	361.4
14	23	0.9480	0.0445	379.2
18	6	0.9705	0.0225	388.2
22	2	0.9826	0.0121	393.1
26	2	0.9895	0.0068	395.8
30	1	0.9935	0.0040	397.4
34	1	0.9959	0.0024	398.4
38	0	0.9974	0.0015	398.9
42	0	0.9983	0.0009	399.3
46	0	0.9989	0.0006	399.5
50	0	0.9992	0.0004	399.7
54	0	0.9995	0.0002	399.8
58	0	0.9997	0.0002	399.9
62	0	0.9998	0.0001	399.9
66	0	0.9998	0.0001	399.9
70	0	0.9999	0.0000	400.0
74	0	0.9999	0.0000	400.0
78	0	0.9999	0.0000	400.0

CDF = cumulative probability distribution function.

Weibull two-parameter cumulative probability distribution function (CDF) using parameter estimates given in table 1, probability distribution function (Probability) for the Weibull two-parameter estimates given in table 1, and the spot size (acres) interval, for illustrative purposes, assuming 400 spots requiring cut-and-leave treatment in a particular region and length of time, in this case 1 year.

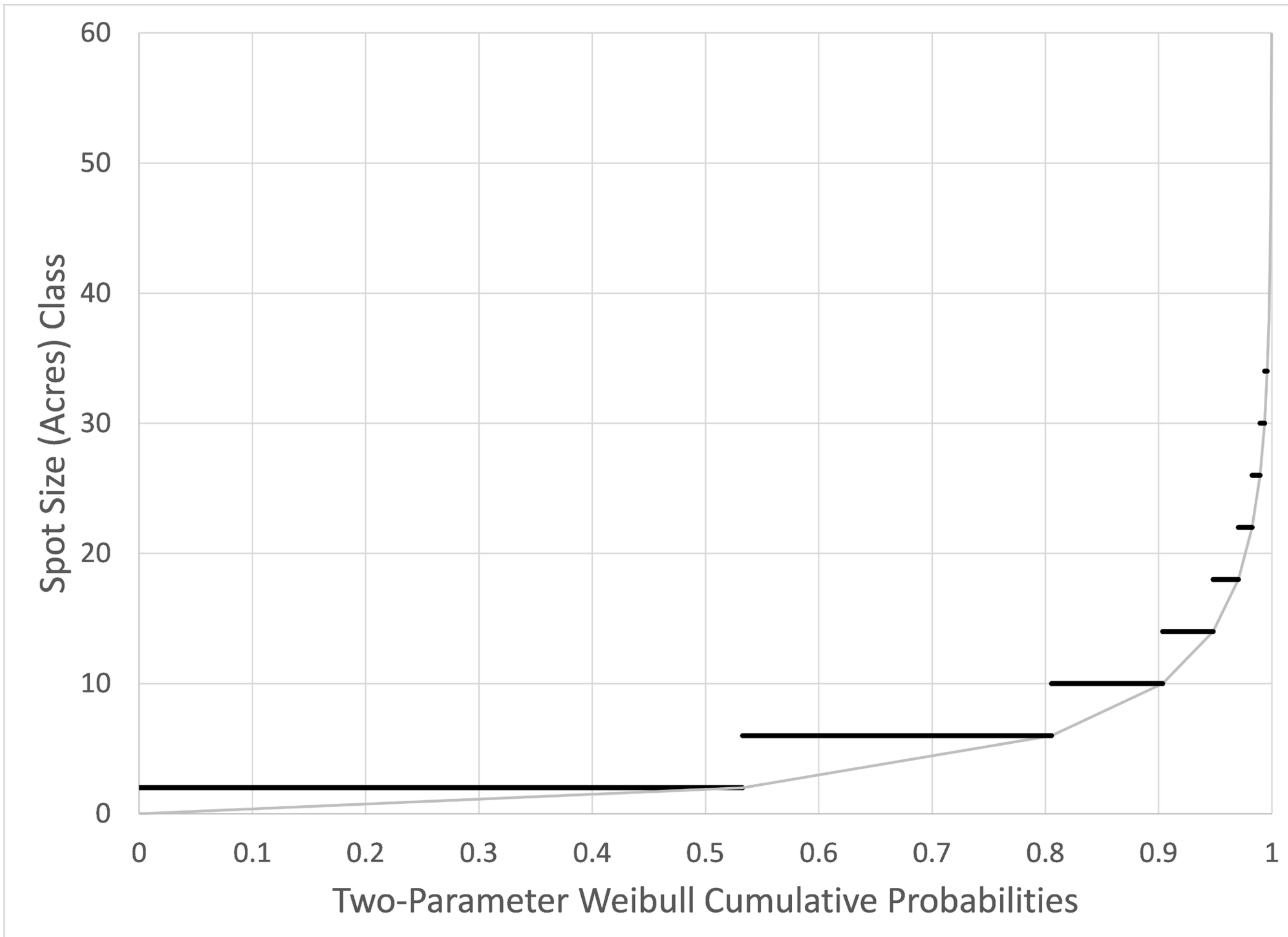


Figure 3—Two-parameter Weibull cumulative probability along with spot size (acres) assignment intervals (bold black lines). To assign an acreage to a particular future southern pine beetle (SPB) spot, a random number is generated from 0 to 1 (e.g., Rand() within Microsoft Excel), and if that random number is 0.5327 or less that SPB spot is assigned an acreage of 2 acres. If that random number is from 0.5328 to 0.8055, the SPB spot is assigned an acreage of 6 acres, and so forth. Consistent with the observed data (*n* = 330)—Table (2), a future SPB spot has a much greater probability of being assigned an acreage of 2 acres (a large interval) than being assigned an acreage of 30 acres (a small interval).

acres, while there is only a 1.21-percent chance of a similarly treated SPB spot being assigned a size of 22 acres. Thus, whenever a random number between 0 and 1 is 0.5327 or less, a SPB spot is assigned a spot size of 2 acres, while if that random number falls between 0.9706 and 0.9826 the spot is assigned an acreage of 22 acres.

Alternatively, we can multiply the 0 to 1 random number by the number of expected SPB spots requiring cut-and-leave suppression measures, for a given region within a particular length of time, and whenever that numerical product falls within a particular SPB spot size acre interval that corresponding acreage is assigned to the SPB spot. Thus, if we expect 400 spots requiring cut-and-leave treatment in the BNF in 2021, for example, we can generate 400 random numbers between 0 and 1, multiply each of the 400 random numbers by 400, and then determine what spot size acre interval those numerical products are within to assign a spot size (acres). The spot size acre intervals correspond to the random number intervals from CDF, and the use of either approach will produce the same treated spot size acreage being assigned to a particular spot. Once again, given the current treated spot size probability distribution (tables 1 and 2, fig. 1), smaller spot sizes (acres) have a wider interval (fig. 3) and hence should be assigned a greater number of times to SPB spots.

As stated earlier, users can alter the spot size (acres) probability distribution in the Excel application if desired, to better tailor the estimates to their particular region of interest and length of time. The Excel application will automatically adjust spot size (acres) assignments.

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