Potential Alternative Tree Species as Substrates for Forest Farming of Log-grown Shiitake Mushrooms in the Southeastern United States

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Summary. **Shiitake (*Lentinula edodes*) is an edible mushroom-producing fungus. "Natural log-grown" shiitake mushrooms are favored by consumers and are often produced by small farmers and hobbyists in the United States. The tree species most often recommended as a substrate for shiitake is white oak (*Quercus alba*), which has many other economic uses. We tested two strains of shiitake in log substrates of three common, low-value tree species in the southeastern United States to identify potential alternatives to white oak. We found that sweetgum (*Liquidambar styraciflua*) was a good substitute for white oak, both in terms of mushroom production and financial returns. Red maple (*Acer rubrum*) had less potential, with lower production and marginal financial returns, and ailanthus (*Ailanthus altissima*) was not a suitable alternative substrate. Of the two shiitake strains tested, a commercially available strain performed better than a naturalized strain that was isolated from an uninoculated log. Further research is needed to identify other potential alternative substrates and production techniques in the southeastern United States and other regions.**

Shiitake (*L. edodes*) is an edible mushroom-producing fungus, used in Asian cuisine and traditional medicine for hundreds of years (Mudge et al., 2013). In 2017–18, U.S. commercial specialty mushroom producers sold $45 million of shiitake (U.S. Department of Agriculture, 2019). Shiitake can be produced on sawdust blocks or natural logs, but log-grown shiitake command a 50% wholesale price premium (Gold et al., 2008). Forest farming of shiitake on logs has become popular among hobbyists and small farmers, as it involves little specialized equipment or labor after inoculation (Gold et al., 2008).

Inoculation involves inserting spawn into holes drilled into logs recently cut from living hardwood trees. Logs do not need to be re-inoculated and can continue to fruit periodically for 3 to 5 years (Frey, 2020). Logs can be obtained from tops and branches, or felled trees, such as from thinning of stands. Thinning of low-value timber trees for shiitake cultivation, to allow the remaining higher-value timber trees greater opportunity to grow, offers a straightforward economic opportunity for some woodlot owners (Bruhn and Hall, 2008; Gold et al., 2008).

Oaks (*Quercus* sp.), particularly white oak (*Q. alba*), are recognized as preferred species for shiitake production in North America (Mudge et al., 2013). White oak is widely distributed throughout eastern North America, typically in mixed midsuccession stands. However, it has a range of other potential uses, including timber. Thus, there has been interest in identifying alternative species for shiitake production (Mudge et al., 2013), but there is limited scientific literature quantifying productivity. Species tested include northern red oak (*Quercus rubra*) and sugar maple (*Acer saccharum*), which demonstrate good potential, whereas american beech (*Fagus grandifolia*), black cherry (*Prunus serotina*), sassafras (*Sassafras albidum*), and american sycamore (*Platanus occidentalis*) have poor potential (Bratkovich, 1991; Bruhn et al., 2003, 2009; Sabota, 1996). Although these species exist in the southeastern United States, none are particularly common throughout the landscape. The objective of our research was to test low-value, common tree species from the southeastern United States as potential alternatives to white oak for shiitake production.

Methods

To provide the most widely applicable results, our experiment mimicked a common management approach used by small farmers and hobbyists, and taught by local cooperative extension services (Frey, 2020).

Location. A field trial was installed on Randolph Experimental Farm near Petersburg, VA, close to the border between the piedmont and coastal plain ecological regions. Most land in the region has a history of farming, but a large portion has regrown to early-to-mid succession forests. The trial was installed near the farm field edge in a wooded area surrounding a small stream, primarily covered with loblolly pine (*Pinus taeda*). This area was chosen because of its moderate-high shade levels and

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.4536	lb	kg	2.2046
1.6093	mile(s)	km	0.6214
0.9072	ton(s)	Mg	1.1023

because a pine-dominated ecosystem was thought to have lower prevalence of hardwood-consuming fungi present that would compete with shiitake.

Species and strain selection. We selected three tree species that are common and have low timber value to compare with white oak as a substrate for shiitake. Sweetgum (*L. styraciflua*) and red maple (*A. rubrum*) are early successional native species that are common in former farm fields and recently cutover forests. Ailanthus (*A. altissima*), also known as "tree-of-heaven," is an invasive exotic species that proliferates around field edges and roads. We tested two "wide-range" strains (referring to the temperature range for fruiting) of shiitake, "West Wind," a popular commercial strain, and "Cismont," a naturalized wide-range strain that was isolated from an uninoculated log in a Virginia producer's log yard. Cismont is assumed to be novel recombinant.

Inoculation and experimental design. In late Winter 2014, ailanthus logs were obtained on-site by harvesting trees from field edges. White oak, sweetgum, and red maple were obtained from a nearby construction site. Logs were inoculated by drilling with a 12-mm-diameter bit with a stop collar set at 25 mm depth, in a 5 × 3-inch diamond pattern. Sawdust spawn were inserted and sealed with cheese wax. Logs were weighed, tagged, and arranged in a randomized block design with three replicates. Ten logs were used for each treatment in each replicate, for a total of 240 logs (4 tree species × 2 shiitake strains × 3 replicates × 10 logs). Logs were stacked log-cabin style.

Productivity testing. Due to personnel changes, no data on production were collected during the 3 years following inoculation in 2014. During this period, the logs were left to fruit naturally. On reengaging the project, individual logs were assessed to determine if forced fruiting was feasible. In Sept. 2017, logs were soaked in water for 24 h at ambient temperature, then stacked in a low-ground A-stack and left for 1 week. Mushrooms were harvested by cutting close to the bark, and the total mushroom harvest from each log was weighed separately. We regressed mushroom production (kilograms) on tree species, mushroom strain, and log length (centimeters). Because many logs did not produce any mushrooms, we used a censored (lower limit 0), linear Tobit regression model with a two-part likelihood function, appropriate for a dependent variable that represents both the probability of production and the amount of production (Tobin, 1958).

Financial analysis. Alternative species to white oak for shiitake substrate may produce a lower quantity of mushrooms per log, but also have a lower purchase or opportunity cost. We conducted a financial analysis using a 500-log shiitake enterprise budget spreadsheet based on Frey (2020) and Szymanski et al. (2003) updated with current prices, available in the supplementary online materials. We estimated prices per standard 25-lb log by species based on sawtimber stumpage prices and costs for felling, loading, hauling, and cutting. We used the budget to estimate net present value (NPV) and discounted returns to labor (DRL) for each species, using a 7% discount rate. DRL is the discounted revenue minus discounted nonlabor input costs, divided by discounted hours of labor, which is the equivalent of a break-even wage rate (Mercer et al., 2014).

Results and discussion

By 2017, of the original 240 logs, 94 were not suitable for forced fruiting. The number of logs that were no longer available for production were distributed fairly evenly across species: 23 ailanthus, 23 red maple, 28 sweetgum, and 20 white oak. In addition, identification tags on five logs (four red maple, one sweetgum) were lost or illegible, meaning that we could not identify the shiitake strain or the original size of the log. Thus, 141 logs were available to test with forced fruiting by soaking. These remaining logs were kept in their original replicate blocks during testing.

A substantial number of logs from each species produced no mushrooms after the soaking, including 35 (95%) of 37 ailanthus, 24 (65%) of 37 red maple, 5 (16%) of 32 sweetgum, and 15 (38%) of 40 white oak. It is not surprising that some logs were no longer productive by the fourth year after inoculation because shiitake consume wood. Logs that persist longer will generate more economic benefits. Thus, both a higher probability of nonzero production in the fourth year and higher production among logs with nonzero production are desirable. Using a Tobit model, we jointly modeled these two outcomes.

Of the logs with nonzero production, ailanthus averaged 0.055 kg/log on 2 of 37 logs, red maple 0.188 kg/log on 13 of 37 logs, sweetgum 0.123 kg/log on 27 of 32 logs, and white oak 0.205 kg/log on 25 of 40 logs (Fig. 1). Nonzero production by shiitake strain averaged 0.217 kg/log for West Wind, and 0.090 kg/log for the Cismont strain, across logs of all species.

Table 1 presents the results of the Tobit regression of mushroom production (kilograms). The coefficients of the Tobit model represent a combination of likelihood to produce mushrooms and the amount of mushrooms produced. Dummies for white oak and West Wind were excluded as baseline categories. These results suggest that sweetgum is a good alternative to white oak, because there is no statistically significant difference in production. Red maple produces moderately less than white oak, and ailanthus substantially less. The West Wind strain generated higher yield. Also, higher yield is achieved on longer logs.

Based on current sawtimber prices for each species, we estimated that a standard 25-lb log would cost $1.23 for white oak, $1.04 for sweetgum, $0.98 for red maple, and $0.74 for ailanthus. For a 500-log operation, this leads to substantial differences in log costs; however, logs are a relatively minor expense in terms of the operation (3% of total costs for white oak). Based on the results of this experiment, combined with Frey (2020) and Szymanski et al. (2003), we estimated that over the course of the 4-year operation, white oak and sweetgum would yield a total of 1.47 kg/log, red maple 0.74 kg/log, and ailanthus 0.03 kg/log. A budget for white oak shows potential profits (Supplemental Table 1). The summary results show positive financial profits also for sweetgum, which are slightly higher than white oak because of lower log costs, but overall losses for red maple and ailanthus (Supplemental Table 2). The results for red

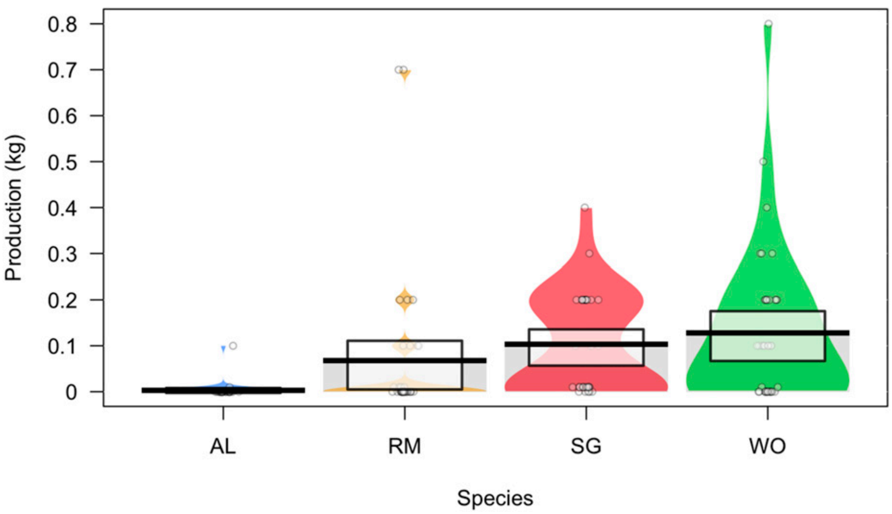

Fig. 1. The mean (horizontal bar in the box), the first and third interquartile ranges (the lower and upper box lines), and the distribution of data points for shiitake mushroom production for ailanthus (AL), red maple (RM), sweetgum SG), and white oak (WO); 1 kg = 2.2046 lb.

Table 1. Results of the Tobit regression of production (kilograms)[z] on tree species, shiitake strain, and length of log.

	Coefficient	SE	*P* value
Ailanthus	–0.315*	0.086	0.000
Red maple	–0.124*	0.055	0.026
Sweetgum	–0.001	0.051	0.977
Cismont strain	–0.140*	0.042	0.001
Log length (cm)[z]	0.004*	0.002	0.010
Constant	–0.378	0.203	0.064
N	141		
Chi-square	59.83*		0.000
Pseudo *R*-square	0.596		

[z]1 kg = 2.2046 lb, 1 cm = 0.3937 inch.
*Significant at $P \leq 0.05$.

maple are borderline, with a negative NPV but positive DRL. This occurs because the DRL lower than the assumed wage rate used to calculate NPV. For ailanthus, both the DRL and NPV are negative.

Conclusions

This short communication reports results of a project to test shiitake production on tree species that could be alternatives to white oak. Although numerous guides have been published on shiitake production in the United States (e.g., Frey, 2020), this study is one of the few quantitative assessments of substrate in the literature, and to our knowledge the only to specifically target common, low-value tree species in the southeastern U.S. coastal plain and piedmont. As such, it can help farmers, woodlot owners, and hobbyists find alternatives where white oak is not readily available, or better use their forest resources by thinning low-value timber trees for shiitake, leaving oak to mature for future harvest.

White oak is widely distributed across the eastern United States, which may be a reason why it has become a preferred substrate for shiitake. Our results suggest that sweetgum is a good alternative to white oak in the southeastern U.S. coastal plain and piedmont. Red maple produced less than white oak, and negative financial profits. Still, red maple might be a reasonable alternative for hobbyists or if logs or other inputs can be obtained more cheaply than assumed in our financial analysis. Ailanthus clearly is not a suitable alternative. Future research on shiitake in the southeastern United States should consider additional species, as well as various production and management approaches, many of which have been never fully assessed in a quantitative way in this region. In addition, further research is needed to identify potential alternative species in other parts of the U.S. white oak range where sweetgum is not common, including the Appalachian, midwestern, and northeastern United States.

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Supplemental Table 1. **Budget for shiitake on white oak. Assumptions and results of budgets for other log species are presented in Supplemental Table 2.**

				Year				
Production		**Units[z]**		**0**	**1**	**2**	**3**	**4**
Logs (no.)		logs		500	490	480	470	400
Mushrooms produced		kg		0	20	450	325	125
Mushrooms sold fresh (20% cull)		kg		0	16	360	260	100
Equipment and materials				**Year**				
Establishment	**Quantity**	**Units[z]**	**Price**	**0**	**1**	**2**	**3**	**4**
Chain saw[y,x]	8	h	2.75	$22				
Drills/angle grinders[y]	40	h	1.5	$60				
Pickup truck[y,w]	300	km	0.36	$108				
Hot plate[y]	40	h	2	$80				
Refrigerator[y,v]	14	d	0.67	$9				
Fresh logs	500	logs	1.23	$615				
Drill bits and adapters	4	sets	50	$200				
Sawdust spawn [5-lb (2.3 kg) bag]	18	bags	22	$396				
Inoculator	5	tools	39	$195				
Cheese wax	1	case	115	$115				
Wax daubers	1	100-count	37	$37				
Water tanks	5	tanks	100	$500				
Coolers	4	coolers	75	$300				
Heavy-duty 100-ft (30.5 m) hose	1	hose	42	$42				
Production and sales	**Quantity**	**Units**	**Price**					
Refrigerator[y,v]	0.5	$d\cdot kg^{-1}$	0.67	–	$5	$121	$87	$34
Pickup truck[y,w]	10	$km\cdot kg^{-1}$	0.36	–	$58	$1,296	$936	$360
Utilities				$150	$150	$150	$150	$150
Boxes	0.8	box/kg	0.75	–	$10	$216	$156	$60
Ice	0.1	$kg\cdot kg^{-1}$	2.2		$4	$79	$57	$22
Subtotal equipment and material costs			$2,829	$226	$1,862	$1,386	$626	
Labor				**Year**				
Establishment	**Quantity**	**Units**	**Price**	**0**	**1**	**2**	**3**	**4**
Prepare site	8	h	10	$80				
Prepare logs	8	h	10	$80				
Drill, inoculate, plug logs	40	h	10	$400				
Stack logs	4	h	10	$40				
Production and sales	**Quantity**	**Units**	**Price**					
General maintenance	0.10	h/log	10	$500	$490	$480	$470	$400
Soak logs	0.10	h/log	10	$500	$490	$480	$470	$400
Harvest	0.13	$h\cdot kg^{-1}$	10	$0	$20	$450	$325	$125
Marketing and sales	0.40	$h\cdot kg^{-1}$	20	$0	$128	$2,880	$2,080	$800
Hauling	0.20	$h\cdot kg^{-1}$	10	$0	$32	$720	$520	$200
Subtotal labor costs				$1,600	$1,160	$5,010	$3,865	$1,925
Total costs				$4,429	$1,386	$6,872	$5,251	$2,551
				Year				
Revenues		**Units**	**Price**	**0**	**1**	**2**	**3**	**4**
Fresh shiitake mushrooms		kg	$30.00	$0	$480	$10,800	$7,800	$3,000
				Year				
Returns estimates				**0**	**1**	**2**	**3**	**4**
Yearly net cash flow				($4,429)	($906)	$3,928	$2,549	$450
Discounted cash flow[u]				($4,429)	($847)	$3,431	$2,080	$343

(*Continued on next page*)

Supplemental Table 1. (*Continued*) Budget for shiitake on white oak. Assumptions and results of budgets for other log species are presented in Supplemental Table 2.

Production		Units[z]	Year 0	1	2	3	4
Break-even yield at this price	683	kg					
Internal rate of return	12%						
Discounted returns to labor[u]	16.45	$/h					
Net present value[u]	578	$					

[z]1 kg = 2.2046 lb, 1 km = 0.6214 mile, 1 d·kg^{-1} = 0.4536 d/lb, 1 km·kg^{-1} = 0.2818 mile/lb, 1 box/kg = 0.4536 box/lb, 1 h·kg^{-1} = 0.4536 h/lb.
[y]Includes depreciation, maintenance, and fuel/electricity.
[x]Estimate based on Miller and Sarles (1986).
[w]Estimates based on Internal Revenue Service (2020).
[v]Estimates based on cost of standard refrigerator assumed $1000 with life of 10 years, energy usage 5 kWh/d * $0.08/kWh.
[u]Assumes 7% discount rate.

Supplemental Table 2. Comparison of key assumptions and results of shiitake budgets on four log species.

	White oak	Sweetgum	Red maple	Ailanthus
Assumptions				
Log price ($/log)[z]	1.23	1.04	0.98	0.74
4-year yield (kg/log)[y]	1.47	1.47	0.73	0.03
Results				
Break-even 4-year yield (kg/log)[y,x,w]	1.37	1.36	0.96	0.58
Internal rate of return (%)	12%	13%	–44%	
Discounted returns to labor ($/h)[x,v]	16.45	16.55	8.59	–5.70
Net present value ($)[x]	$578	673	–3621	–7626

[z]Estimate based on price of sawtimber stumpage from TimberMart-South (2020). $48 per ton white oak, $33 sweetgum, $28 red maple, $9 ailanthus, plus $40 per ton for cutting, hauling, and delivery. May vary depending on availability of logs. Alternatively, this cost could represent the opportunity cost of the wood plus the labor required to fell and skid trees; $1/ton = $1.1023/Mg.
[y]1 kg = 2.2046 lb.
[x]Assumes 7% discount rate.
[w]The yield at which, given all the other assumptions, net present value would be exactly zero. An actual yield higher than this would represent a positive profit.
[v]The wage rate at which, given all the other assumptions, net present value would be exactly zero. An actual wage rate lower than this would represent a positive profit.