Strain of Shiitake Mushroom [*Lentinula edodes* (Berk.) Pegler] and Wood Species Affect the Yield of Shiitake Mushrooms

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ADDITIONAL INDEX WORDS. sweetgum, *Liquidambar styraciflua*, biological efficiency, alternative crops

SUMMARY. Logs of white and red oak (*Quercus* spp.), black cherry [*Prunus serotina* (Ehrh.)], sassafras (*Sassafras albidum* (Nutt.) Nees), and eastern sycamore [*Platanus occidentalis* (L.)] were inoculated with eight strains of shiitake mushroom in 12-mm holes drilled 25 mm deep and spaced 15 cm apart down the log and 5 cm apart around the log in a staggered pattern. Logs then were placed in quonset houses covered with 80% shade cloth in Mar. 1991. The environment within these shaded houses was not modified otherwise. Harvested mushrooms were counted and weighed and biological efficiency (BE) was determined. White and red oaks produced significantly higher yields of shiitake mushrooms over the lifetime of the log than the other types of wood. Only one strain, CW25, produced significantly lower yields than the best four strains. Interactions among strains and seasons of harvest and the species and seasons of harvest were significant. The most productive mushroom strains and tree species yielded more mushrooms later in the life of the logs than the least productive strains and tree species did earlier in the life of the logs. BE attained from strain $\times$ species interactions

ranged from 0% (WW70, CW25, and WR85 on sycamore) to 8.8% (WW44 on red oak) in an outdoor noncontrolled environment. The gross per cord value (at wholesale price) of shiitake harvested from white oak was \$2475.00. The cost of producing one cord of shiitake is about \$6.44 per log in a small-scale operation. A net return of \$1509.00 per cord is realistic and includes the cost of labor.

The search for alternatives to traditional low-profit livestock and row-crop farming enterprises has focused on producing specialty horticultural crops with potential to alleviate cash-flow problems experienced by many small and limited-resource farmers. The United States imports $\approx$ 90% of the shiitake mushrooms consumed domestically or about \$1 billion worth of mostly dried product per year (Turner, 1988). From 1994 to 1995, 5.2 million pounds of domestically produced shiitake mushrooms were sold for \$20 million, an increase of 94% in production and 93% in sales value from 1992 to 1993 (National Agricultural Statistics Board, 1995).

Since 1987, Alabama A&M Univ., in conjunction with several other organizations, has facilitated the integration of shiitake mushrooms into local farming systems. Such integration uses existing forest resources and capitalizes on a crop that is primarily imported but could be grown domestically. Many small-scale farmers have expanded their shiitake operations beyond the demonstration stage. Currently, there are >100,000 inoculated logs in Alabama; accounting for 10% of the inoculated logs in the United States (National Agricultural Statistics Board, 1995). Production potential of these logs over their 3- to 4-year production period is $\geq$ 100,000 pounds of fresh shiitake mushrooms.

As producers across the southeastern United States begin to commercialize their operations, there are more questions about shiitake strain, wood species, and interaction of the two. My objectives were 1) to determine the most efficient and productive tree species for shiitake production and 2) to evaluate eight shiitake spawn strains to determine the most productive strains for each tree species in a southeastern U.S. climate.

Materials and methods

Dormant black cherry, sassafras, eastern sycamore, and red [*Quercus falcata* (Michx.)] and white oak [*Quercus muehlenbergii* (Engelm.)] trees were felled in Feb. 1991 in northern Alabama on the Alabama A&M Univ. campus. Tree diameter breast high ranged from 15 to 30 cm. Whole trees were left in the woods for 1 month. Trees then were cut into logs 102 cm in length and were inoculated over the next 7 d. The average log weight was 14.5 kg.

Before inoculation, each log was weighed and tagged with a treatment number. Holes (12 mm in diameter) were drilled with a 6.5-mm, 8000-rpm high-speed drill (Makita Electric Works, Japan) and a 12-mm, soft-steel screw tip bit with stop collar (Field and Forest Products, Peshtigo, Wis.) 25 mm deep into the logs. Number of holes drilled per log varied with log diameter, but holes were generally 15 to 20 cm apart within a row traversing the length of the log. Since mycelium travels easily with the wood grain, but very slowly across the grain, alternate rows were staggered, forming a diamond pattern with each row 2.5 to 5 cm apart around the log.

INOCULATION. Immediately after the holes were drilled, logs were inoculated with sawdust spawn purchased from Field and Forest Products (Peshtigo, Wis.). A thumb style brass inoculator was used to insert the spawn into holes (Field and Forest Products). The following shiitake strains were evaluated: WR46 (wide range, 10 to 24 °C), V3 (warm weather, 10 to 25 °C), WW44 (warm weather), West Wind (wide range), Twice Flowering (cold weather/5 to 18 °C), WW70 (warm weather), CW25 (cold weather), and WR85 (wide range). Each log was inoculated with one shiitake mushroom strain. To reduce moisture loss and to keep the spawn in the holes, each hole was covered with hot (177 °C) cheese wax (Kelly Supply, Abbotsford, Wis.) using an aluminum turkey baster. Ends of the logs were dipped in wax to reduce moisture.

Each of the five wood species was inoculated with eight strains of shiitake mushroom spawn, and each strain $\times$ spawn interaction was replicated four times. Thus, for each of the five tree species, 32 logs were inoculated. A total of 160 logs were inoculated in

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Contributed by the Agricultural Expt. Station, Alabama A&M Univ. journal no. 282. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked advertisement solely to indicate this fact.

this experiment (five wood species $\times$ eight shiitake strains $\times$ four replications).

LOG MANAGEMENT. Logs were placed on steel rails and stacked in a crib stacking configuration (example, the first row of five to six logs were placed in a north-south direction, the second in an east-west direction, etc., with the height of the stack $\approx$ 4 feet). The stacks were sheltered yearround by an 80% polypropylene shade cloth (Cassco, Gadsden, Ala.) covering a 7.3-m-wide $\times$ 18.3-m-long $\times$ 4.6-m-high quonset greenhouse to provide protection from wind and sun. The shade cloth covered the south end and east and west sides of the house. The stacks of logs were covered with a white fruiting blanket made of a dense, nonwoven polypropylene fabric (Synthetic Industries, Chattanooga, Tenn.) to conserve moisture and moderate the temperature of the logs. The blanket was removed if *Trichoderma viride* (Persoon : Fries) appeared on the surface of the logs, if the bark was too wet, and before soaking to initiate fruiting.

Summer temperatures $>38^{\circ}\text{C}$ can heat up and dry out the logs sufficiently to kill the spawn; therefore, logs were overhead-irrigated (Dramm nylon 180° nozzles; Cassco, Gadsden, Ala.) to maintain moisture and reduce log temperature. To determine moisture loss, logs were “hefted,” and if the weight was apparently too low, logs were irrigated. Small diameter logs (<13 cm) dried out much faster than larger diameter logs. Also, during the summer, logs were misted two to three times weekly (4 to 6 h each time) and when daytime temperatures were $>32^{\circ}\text{C}$.

To initiate fruiting, logs used in shiitake production generally are soaked (Przybyłowicz and Donoghue, 1990). The first soaking in these tri-

als occurred in Oct. 1991. Logs were unstacked and set in 1135-L aluminum soak tanks (the same type used to water livestock) for 48 to 72 h. Soaking was repeated four times through the year each year to increase moisture content or to initiate fruiting. Between soakings, log moisture content was maintained during the 36-month trial by overhead irrigation or misting. Beginning in 1992, overhead irrigation

Table 1. Shiitake mushroom fresh weight, number of shiitake produced, and biological efficiency (BE) for four log weight categories.

Green log wt class (kg/log)	Harvested yield ^a		
	Mushroom fresh wt (g/log)	No. mushrooms/log	BE (%)
1-44	122 a	12 a	3.1
45-88	288 ab	24 ab	3.3
89-132	374 bc	33 b	2.7
>132	551 c	33 b	2.9
Analysis of variance			
P value	0.001	0.015	NS

^aValues followed by different letters are significantly different at $P \leq 0.05$ according to Duncan's new multiple range.

Fig. 1. Total grams of mushrooms per log harvested by wood species. Mean separation signified by different letters was determined according to Duncan's new multiple range ($P = 0.0001$).

was applied in the afternoons when ambient temperatures were $>35^{\circ}\text{C}$ using oscillating lawn-type sprinklers.

COMPUTING LOG MOISTURE. To compute biological efficiency, it is necessary to know the dry weight of the inoculated log. Three trees of each of the five wood species were harvest 3 years after the original logs were harvested but at the same time of year. From each tree a circular disk (≈ 5 cm thick) was cut from the end of each 102-cm log cut from the length of each of the tree species. The tree was felled 46 cm above the ground. From five to 10 logs were cut from each tree, depending on its height. The distance from the tree stump to each disk location was recorded, and the disk was labeled to determine if the disk's location relative to tree height affected its moisture content. Disk fresh weight was taken, and then each disk was dried in a 93°C oven. Drying time varied depending on the size of the disk. Each disk was weighed every 12 h. When there was no further weight

loss, the disk was considered dry, and its weight was recorded as dry weight. Percent dry weight was determined by measuring the amount of moisture lost and dividing it by the original wood weight multiplied by 100.

BIOLOGICAL EFFICIENCY (BE).

The BE of a log is a measure of how effective a unit dry weight of wood is in producing mushrooms. BE often is used in reporting research data because it removes the variation that may be introduced by log size. Using the trees discussed under "Computing log moisture" to determine BE in this study, each tree within a species was considered a replicate and each disk within a tree a subsample. The mean dry weight of each wood species was calculated from the disks. Analysis of variance (ANOVA) was performed for species and disk location relative to tree height.

The fresh weight of each inoculated log was multiplied by the calculated percent dry weight for the appropriate species. This calculation

resulted in the dry substrate weight used to compute the BE.

HARVEST. Logs were soaked when volunteer mushrooms started to appear, which typically occurred in the spring and fall. Mushrooms that fruited in the winter or summer were so few that they were combined with the spring or fall data, whichever was closest in time. Production began in Mar. 1992. The harvest seasons were Spring 1992, Fall 1992, Spring 1993, Fall 1993, and Spring 1994. Only no. 1 marketable mushrooms (i.e., those 2.54 to 7.62 cm in diameter with $>25\%$ cap curl) were weighed and counted for each log. These weights and numbers and the calculated BE were recorded for the total production period and by fruiting season. Since there is a continuous market demand for log-grown shiitake mushrooms (producers in Alabama cannot meet demand), it was assumed that all no. 1 mushrooms could be sold at the national average market price, although Alabama producers are receiving \$2.00

Fig. 2. Percent of total shiitake mushroom weight harvested per season by wood species. The "0" line is the break between Spring 1993 and Fall 1993 yields. Note that the lower-yielding wood species produced most of their total yield within the first three harvests. Seasonal yields ($P=0.0001$) and the interactive effects of season and wood species ($P=0.0001$) were significant.

Fig. 3. Total grams of mushrooms harvested per log as influenced by shiitake mushroom strain. Mean separation signified by different letters as determined according to Duncan's new multiple range ($P = 0.024$).

to \$4.00 more per kilogram than the national average.

The experiment was treated as a completely randomized design. ANOVA was calculated for the number of mushrooms harvested per log, the total weight of mushrooms harvested (yield in grams per log), and BE. Means were separated using Duncan's new multiple range as modified by Kramer in 1956 (Gagnon et al., 1989).

Results and discussion

PRODUCTION BY WOOD SPECIES.

Red oak and white oak produced significantly more mushroom total weight per log than cherry, sassafras, and sycamore (Fig. 1), and cherry yielded more than sycamore. The mushroom yield per cord (150 + logs, 15 cm in diameter, and 1 m long) ranged from 82 kg (180 pounds) for white oak to 5.2 kg (12 pounds) for eastern sycamore. In single-log observations, San Antonio (1981) found that red and white oak generally were the most productive regardless of shiitake strain. However, Haney (1989), using spawn strains developed in the 1980s, observed that sycamore and poplar performed as well as or better than white oak. Therefore, it is important to con-

sider as many spawn strain $\times$ tree species interactions as possible to determine optimal production levels. In my experiment, I found no significant wood species $\times$ shiitake strains interaction. Perhaps a broader strain selection would have resulted in greater variation since all of these strains originated from Field and Forest Products.

The onset of fruiting of white oak logs was slower than that of the other four species (Fig. 2). Red oak, cherry, sycamore, and sassafras produced most of their total yield within the first three harvests. Spawn run, and therefore onset of shiitake mushroom fruiting, are typically slower in more dense wood (Przybylowicz and Donoghue, 1990). Chinkapin oak is more dense (in $\text{kg} \cdot \text{m}^{-3}$) (869) than red oak (692), cherry (579), sassafras (499), and sycamore (564) (Davis and Davis, 1986). The greater density may be the reason that white oaks took longer to produce in this study.

The time from inoculation to first fruiting is important to a producer trying to market a crop in a short time. Although the productivity of other species may not be as good as that of oaks, earlier production (up to 1 year) can make a considerable difference in debt repayment and reinvestment for

expansion. In this study, red oak produced 65% or 348 g/log by the end of the Spring 1993 harvest, while white oak only produced 45% or 245 g/log in the same time. If 300 logs were in production, red oak would have produced 31 kg or \$341 more in returns at the end of Spring 1993 than white oak. Therefore, choosing a mixture of wood species with characteristics of early, mid-, and late fruiting onset and reasonable yields may be more profitable in the short run.

PRODUCTION BY SHIITAKE STRAIN.

Grams per log of shiitake mushrooms produced were significantly greater for strains WR46, WW44, WW70, and V3 than CW25 (Fig. 3). The yield per cord of the eight strains ranged from 65 (143 pounds, WR46) to 4 kg (9 pounds, CW25). At the wholesale market prices for the year the shiitake mushrooms were harvested (Fall 1991 to Summer 1992, \$8.20/kg; Fall 1992 to Summer 1993, \$8.82/kg; Fall 1993 to Summer 1994, \$8.55/kg), gross returns would be \$550 for one cord of wood inoculated with WR46. In a 1989 study, Bratkovich (1992) evaluated small-diameter oak logs using seven spawn strains. From the S-1 strain, he harvested 432 pounds (196 kg) of fresh shiitake per cord (320

small-diameter logs in a cord) over 3.5 years. The gross value of mushrooms from this cord at the 1989 average wholesale price of \$4.70 was \$2030.00.

There was greater variability for harvest yield among seasons than among strains (Fig. 4). The high yielding strains (WR46, WW44, WW70, and V3) generally produced the greatest amount (38% to 64% of total yield) during the last two harvests, 24 months after inoculation. The four least productive strains produced 53% to 99% of their mushroom weight per log in the first three harvests, during the first 24 months after inoculation. From data in previous demonstration trials in which yields of strains harvested for the first time six or twelve months after inoculation were compared, it was suggested that delayed harvest resulted in higher later and total yields (Kozak, personal communication).

LOG MOISTURE. Moisture content found in the different wood species varied significantly. Eastern

sycamore had the highest moisture content followed by cherry, red and white oak, and sassafras. The moisture content relative to the height of the tree at which the sample was taken and the height of sample $\times$ species interaction were not significantly different. Similar moisture levels were obtained for red (42.5%) and white (41.5%) oak in a study by Gilbert (1992). Sycamore, cherry, and sassafras were not included in Gilbert's study. Determining log moisture is important for using the computation of BE.

BE. The logs in this experiment were grouped by fresh weight into four categories (<44, 45 to 88, 89 to 132, and >132 kg). For each category, the average fresh weight of mushrooms per log and the average number of mushrooms per log harvested were determined, as well as the average BE per log (Table 1). As would be expected, the larger the log, the greater the actual weight, and in some cases the number, of mushrooms harvested

per log. The differences among the log weight categories were significant for yield and numbers. Expressing yield in terms of BE, however, removed this variation, resulting in no significant differences among log weight categories. Therefore, using the BE to represent yields removed variances that may have occurred if, by chance, one treatment had a disproportionate number of large or small logs.

The BE of each wood species ranged from 0.95% to 5.23%. The BEs of sassafras and sycamore were significantly lower than those of cherry and the oaks. The calculated BE varied only slightly from the actual yield per log data (Fig. 1).

Donoghue (1994a) showed that some wood species and strains can be forced to fruit five to eight times per year in an indoor facility, resulting in a BE of $\leq 30\%$ over 2 to 5 years. However, such management would require a controlled indoor environment (467 m² for 10,000 logs), which would in-

Fig. 4. Percent of total shiitake mushroom weight harvested by season and strain. The "0" line is the break between Spring 1993 and Fall 1993 yields. Note that the lower-yielding strains produced most of their total yield within the first three harvests. Seasonal yields ($P = 0.0001$) and the interactive effects of season and shiitake strains ($P = 0.0051$) were significant.

clude the costs of facility construction of about \$15,000 (Donoghue, 1994b).

The pattern exhibited by the BE of the strains varied only slightly from the pattern of the overall mushroom yields per log (Figs. 3). WR46 was not as biologically efficient as its yield would indicate. Although it had the highest yield per log, it ranked only fourth highest in BE. With the exception of CW25, all strains were suitable for the wood species on which they were grown. However, for optimized commercial production, only the white and red oak should be considered as a substrate based on the results of this experiment, which is not to the exclusion of wood species not evaluated in this research. These strains were selected based on their fruiting temperature requirements.

At the end of 36 months, the most productive log species were red oak and white oak. The most productive strains were WR46, WW44, WW70, V3, WR85, and Twice Flowering. Although the wood species and strain interactions were not significant, BE attained from these interactions ranged from 0% (WW70, CW25, and WR85 on sycamore) to 8.8% (WW44 on red oak) in an outdoor uncontrolled environment. The gross per cord value (\$8.14/kg) of shiitake harvested from white oak was \$1332. Since white oak trees harvested for shiitake are not large enough to be considered for timber, they have a pulpwood value of only \$6 per cord. The costs, from inoculation to production, for one cord of shiitake are about \$6.44 per log in a small-scale operation (Sabota, 1993). A larger operation would have most of the same costs and would reduce the actual production costs per log. The costs include the following: one cord of logs, \$100; spawn, \$88; wax, \$6; shade cloth, \$75; high-speed drill, \$300; two spawn guns, \$44; two drill bits, \$24; two metal wax basters, \$16; four drilling stands or saw horses, \$50; stove to melt wax, \$20; propane fuel, \$12; 1135-L soaking tank, \$116; irrigation hoses and sprinklers, \$40; and inoculation labor, \$225. Assuming a \$2475 return (150 logs yielding 0.5 kg per year for 3 years and selling for \$11/kg) and a cost of production of about \$966 per cord, a net return of \$1509 per cord is realistic and includes the cost of preharvest labor. However, it is important to note that many produc-

ers have gone out of shiitake production due to limited markets in their growing areas and the labor requirements for harvesting, grading, soaking, marketing, and delivery. The success of the shiitake mushroom industry in Alabama is due, in part, to the cooperation among growers in merging product to meet large market demands. This allows producers to maintain markets even when one producer falls short on production occasionally.

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Temperature and Photoperiod Affect Grafted Cactus Scion Necrosis

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ADDITIONAL INDEX WORDS.

Chamaecereus silvestrii, *Hylocereus trigonus*, irradiance, rootstock, axillary branching

SUMMARY. The interaction among temperature, photoperiod, and irradiance on survival of *Chamaecereus silvestrii* (yellow sport) flat-grafted onto *Hylocereus trigonus* Haw. rootstock was studied in an effort to understand the basis for elevated scion necrosis during winter. Plants were placed in glasshouses maintained at 12, 16, 20, or 24 °C under either daylight (moles per day), 66% daylight or daylight + 100 $\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ irradiance levels. Plants were grown with an 8-hour (short day) or 8-hour + 4-hour night interruption (long day) photoperiod. Cactus scion necrosis increased under short days and a growing temperature of 12 °C and was nearly eliminated by long-day conditions and a growing temperature of 16 °C. Irradiance did not affect scion necrosis. Plant quality rating was highest when plants were grown under long-day conditions at 16 °C.

Grafted cacti are sold as a novelty crop throughout the world. A common rootstock for grafted cacti is *Hylocereus trigonus* Haw. (Night Blooming Cereus) (Lamb and Lamb, 1976), an epiphytic cactus native to tropical America (Cullman et al., 1984). *Gymnocalycium mihanovichii* var. *friedrichii* 'Hibotan' (red) and *Lobivia* (*Chamaecereus*) *silvestrii* Br. and R. (yellow sport) commonly are grafted onto *H. trigonus* because of

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Minnesota Agricultural Expt. Station no. 21,848. I acknowledge Nurseryman's Exchange for donating plant material. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked advertisement solely to indicate this fact.