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

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**Summary.** Logs of white and red oak (Quercus spp.), black cherry (Prunus serotina Ehrh.), sassafras (Sassafras albidum Nutt.), and eastern sycamore (Platanus occidentalis L.) were inoculated with eight strains of shiitake mushroom spawn purchased from Field and Forest Products, Peshtigo, Wis. (common name: mushroom spawn, also known as liquidambar styraciflua, biological efficiency, alternative crops). Additional Index Words. Mushrooms, Shiitake, Wood species (Berk.) Pegler

**Materials and methods.** Dormant black cherry, sassafras, eastern sycamore, and red oak (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 × 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
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 = 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 °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 °C.

To initiate fruiting, logs used in shiitake production generally are soaked (Przybylowicz and Donoghue, 1990). The first soaking in these trials 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 was supplemented with overhead-irrigation (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 °C.

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

<table>
<thead>
<tr>
<th>Green log wt class (kg/log)</th>
<th>Harvested yield (g/log)</th>
<th>No. mushrooms/log</th>
<th>BE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–44</td>
<td>122 a</td>
<td>12 a</td>
<td>3.1</td>
</tr>
<tr>
<td>45–88</td>
<td>288 ab</td>
<td>24 ab</td>
<td>3.3</td>
</tr>
<tr>
<td>89–132</td>
<td>374 bc</td>
<td>33 b</td>
<td>2.7</td>
</tr>
<tr>
<td>&gt;132</td>
<td>551 c</td>
<td>33 b</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Analysis of variance

| P value | 0.001 | 0.015 | NS    |

*Values followed by different letters are significantly different at P \leq 0.05 according to Duncan's new multiple range.*
was applied in the afternoons when ambient temperatures were >35 °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 harvested 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
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 lb). 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 consider as many spawn strain × tree species interactions as possible to determine optimal production levels. In my experiment, I found no significant wood species × 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 kg·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.

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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 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 x 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 ≤30% over 2 to 5 years. However, such management would require a controlled indoor environment (467 m² for 10,000 logs), which would in-
include 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 T twice flowering. Although the wood species and strain interactions were not significant, BE attained from these interactions ranged from 6.6% (WW70, CW25, and WR85 on scymore) to 8.8% (WW44 on red oak) in an outdoor uncontrolled environment. The gross per cord value ($5.14/ 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 scale 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, $58; wax, $6; shading cloth, $75; high-speed drill, $300; two saw guns, $44; two drill bits, $24; two metal wax baskets, $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 producers 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.

### Literature Cited