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PROJECT TITLE: Development of a swath harvesting system for maintaining grain quality in the field.

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OBJECTIVES AND EXPERIMENTS CONDUCTED BY LOCATION TO ACCOMPLISH OBJECTIVES:

Objectives for 1987 were to

1. continue the experimental evaluation of the modified swath harvesting concept for rice, and

2. perform an economic analysis of the modified swath harvesting concept based on experimental results.

During 1987 a third experiment of modified swath harvesting techniques was completed over a total 18 day period beginning on 18 September. This experiment included head rice evaluations for open and covered windrows as well as direct harvested grain. A medium grain (M202) cultivar was used, and tests were conducted over 2 ha (5.1 acres) located in the Yolo bypass and operated by Heidrick Farms, Inc., Woodland, CA.

The results of the 1987 trial were combined with the results of the 1985 and 1986 field trials to perform an economic analysis of the modified swath harvesting concept compared to direct harvesting. The following section includes a complete description of the experimental results (as well as summary data for the 1985 and 1986 trials because of their importance to the economic analysis). A description of the economic model developed and the results obtained is also included.

A swather mounted windrow covering mechanism was also designed during 1987. Portions of this design have been fabricated, but a test of the unit has not yet been possible.

SUMMARY OF 1987 RESEARCH:

Background

Higher drying costs associated with increasing costs of energy have prompted an examination of alternative grain drying techniques, including a return to natural drying achieved by swath harvesting the rice. In California with good weather, the grain moisture content can be reduced significantly with only one day of exposure, and reduced to acceptable storage moistures within three days of exposure, eliminating the drying cost and leaving only the handling and storage charge at the mill. Growers pursuing this technique have found that it can give them greatly improved control over timing of the harvest, thereby reducing equipment demands at critical harvest periods.

The mechanisms typically employed to swath the rice and form the windrow place the grain at the surface of the windrow. The quality of the rice is seen to deteriorate considerably with continuing exposure past the first day. The principal measure of rice quality is the whole kernel, or head rice yield obtained at milling. Revenue from the sale of the grain is based on the mass fractions of head and broken kernels in the total milled rice (see equation [1], following). Continuing exposure of the grain in the windrow results in decreasing head rice yields. The probable cause of this decrease is the repeated diurnal rewetting of the grain. Rewetting is well known to cause fissuring of dried grain kernels, and is a purported major cause of head rice declines in unharvested standing grain after attaining a critical average moisture content sometime after maturity.

A number of factors are believed to influence fissuring of the grain kernel. Most important appear to be the moisture generated stresses caused by adsorption (Kondo and Okamura, 1930; Kunze and Hall, 1965; Kunze and Hall, 1967; Kunze and Choudhury, 1970; Kunze and Prasad, 1978) and possibly desorption (Bhattacharya, 1980) of moisture. Temperature may also have some influence, but the effect is likely much smaller than that of moisture (Kunze and Hall, 1967; Bhattacharya, 1980). Fissured kernels do not necessarily break during milling, but there appears to be a strong correlation between the level of fissuring and the head rice yield (Rhind, 1962; Craufurd, 1963; Bhattacharya, 1980). A critical moisture is believed to exist below which a kernel will fissure if rewetted (Stahel, 1935; Craufurd, 1963; Rhind, 1962; Kunze and Choudhury, 1970; Bhattacharya, 1980; Siebenmorgen and Jindal, 1986). This critical moisture is suggested to lie in the range of 13 to 16% wet basis. A possible mechanism relates to the elastic properties of the grain, the starch gel being plastic above this moisture and brittle below this moisture (Rhind, 1962). Mechanical properties of the grain and the relationship to stresses developed within the kernel have been explored in an attempt to understand the fissuring processes (Kunze and Choudhury, 1970; Sokhansanj and Gustafson, 1979; Kunze, 1983). Not all varieties of rice are equally susceptible to fissuring (Bhattacharya, 1980; Geng, et al., 1984; Kunze, 1985; Chattopadhyay and Kunze, 1985).

An optimal (on the basis of head rice yield) moisture content for harvest of standing grain is perceived to lie at moistures above the critical moisture content just described. Typical optimum harvest moistures for short and medium grain varieties are reported to be in the range of 20 to 26%, while long grain varieties may have optimal harvest moistures down to perhaps 18% (Bhattacharya, 1980; Chau and Kunze, 1982; Geng, et al., 1984). All grain kernels on the panicle do not mature uniformly, nor are all panicles at equal levels of maturity. If the harvest is too early, there may be a large fraction of immature kernels, and if too late, many of the kernels may have passed the critical moisture and become damaged.

A practical consequence of all this is that grain exposed either in the unharvested crop or in the windrow is subject to damage by fissuring and cracking, most likely by processes associated with repeated wetting and drying of grain. Further damage may be incurred through harvesting, drying, and handling, particularly if performed improperly. Methods to reduce the environmental damage to the rice, short of parboiling to repair the damage (Chattopadhyay and Kunze, 1986), could potentially increase the value of the grain substantially. Spreading sheets over the standing crop to reduce condensation (dew) on the grain has been evaluated experimentally. Bainer (1932) observed a greater level of fissuring in the upper layers of windrows compared to the lower layers and described an attempt of one grower to manufacture (unsuccessfully) a machine that would invert the windrow to place most of the grain on the lower surface. Bainer did not attribute the fissuring damage to moisture adsorption or dew formation on the upper surface, but instead to the direct exposure to the sun and the more rapid drying rates occuring because of the higher temperatures developed on the surface. As indicated previously, the higher temperatures are probably of lower importance than the rewetting of the grain in the windrow.

Since Bainer's description of a windrow inversion device in 1932, a number of similar, but unsuccessful, attempts have been made to develop such a device. Handling of the windrow can cause substantial grain losses, offsetting the economic benefit obtained by improving the head rice yield of the rice.

The current work is aimed at the development of a process for covering windrows to reduce the quality deterioration of the grain in the windrow without reducing the drying rates of the grain relative to open windrows. The method does not appear to contribute to increased grain losses from the windrow, yet can be performed mechanically. Results of the 1987 field trial, in addition to brief summaries of the two previous field trials, are presented. An economic model of the process has been developed to determine when the modified swath harvesting technique has the potential to improve the net grain value relative to direct harvesting. Currently, an improved mechanism to be mounted on the swather is under development to test the modified technique on a larger scale.

Experimental Evaluation of Modified Swath Harvesting Techniques

Two methods have been tested for modifying the windrow in an attempt to improve the grain quality over prolonged exposures: 1. folding the windrow to position the grain in the center between layers of straw, and 2. covering the windrow with a layer of stubble cut from either side of the windrow. The first concept was tested during the 1985 season. The second method has been tested over two seasons, one in 1986 and one in 1987. The latter method is mechanically simpler to achieve, does not appear to significantly affect harvester capacity or drying rate in the windrow, reduces grain loss associated with handling of the widrows, yet maintains higher head rice yields compared to open windrows over all moisture contents, and higher head rice yields than direct harvested medium grain rice at low moistures.

Initial Field Trials (1985, 1986):

The 1985 tests were performed during mid-September by starting swathing in M201 rice at 30% moisture content (wet basis) and either immediately folding the windrows or waiting one day following swathing and then folding. Open windrows were also left as controls. A total of 0.8 ha (1.9 acres) were swathed. Windrows were harvested after 1, 2, 3, and 4 day exposures using a rasp bar harvester operated at 500 rpm cylinder speed. Grain samples were collected from the grain auger in the grain tank, returned to the laboratory, ambient air dried to less than 14% moisture, and milled (USDA, 1977). Head rice, total rice, and dockage were determined for each sample. Windrows were rethreshed after several days of drying to estimate theshing loss. Straw moisture content was recorded over the course of the experiments. A weather station recorded environmental conditions, with load cells used to obtain drying rate data for the open and folded treatments. A complete description of the 1985 tests is given by Jenkins (1986).

Summary results from these trials are included in Figs. 1 - 3. Head rice yields from the folded windrows showed a significantly slower decline over time compared to the open windrows (Fig. 1). Grain and straw moisture remained substantially higher in the folded windrows than in the open windrows (Figs. 2 and 3). The dense narrow windrows were also more difficult to thresh than the open windrows, and reduced the harvester capacity.

The 1986 field trials during mid-October involved covering windrows of M9 rice with stubble cut from either side with a 1.8 m (6 ft) wide flail chopper. A total of 1.5 ha (3.7 acres) were swathed. Alternating windrows were treated, leaving open windrows as controls. The chopped stubble was pneumatically conveyed to a spreader mechanism providing a uniform coverage of the windrows. The chopper was of towed type, and the covering operation was done immediately after the swather had formed the windrows. The chopper recovered approximately 560 g/m dry basis (0.4 lb/ft) on a full width of cut, and with a bulk density of 14.5 kg/m^3 (0.9 lb/ft^3) dry basis, left a cover 26 to 52 mm (1 to 2 inches) deep over the grain in the windrow, consistent with observations of the windrow. Windrows were harvested at 1, 3, 5, 7, and 9 days following swathing. Harvesting was performed with a spike tooth harvester operated at cylinder speeds ranging from 800 to 1050 rpm. Grain samples were also collected from the auger in the grain tank, returned to the laboratory, ambient air dried to less than 14% and milled. Windrows were rethreshed at 1100 rpm cylinder speed to estimate threshing loss. Moisture content of the straw was recorded throughout the test.

Environmental and drying rate data was also recorded. A full description of the 1986 trials is found in Jenkins (1986).

Summary results of the 1986 trial are included in Figs 4 - 6. Over the entire 9 day period there was no significant drop in head rice yields for the covered windrows. No significant decrease was seen in the open windrows until after 5 days of exposure. The differences between this trial and the 1985 trial were ascribed in part to the difference in weather--the 1985 test occurring during a period with wider fluctuations in air humidity, heavier dews, and faster drying rates during the mornings; the 1986 test occurring during a cooler period of the year, with a different type of cylinder, and with a rice variety requiring fairly high cylinder speeds for adequate separation. A light rain occurred during the evening of the eighth day, causing the moisture content of the grain and straw to increase somewhat. At harvest (2:00 p.m.) on the ninth day, the moisture content of the grain in the open windrows was slightly higher than that in the covered windrows, although not significantly.

Field Trials (1987):

A more extensive test of the covered windrow concept first tested during 1986 was conducted from 18 September to 6 October 1987 with variety M202, also a medium grain rice. A total area of 2 ha (5.1 acres) were swathed. The same mechanical means of covering windrows with stubble used during the 1986 trials was used during the 1987 trials. Alternating windrows were treated, with open windrows remaining as controls. Twelve windrows, each 305 m (1000 ft) in length were formed on 18 September. Header width of the swather was 4.88 m (16 ft). Two adjacent windrows were harvested on each of days 1, 3, 6, 8, 12, and 17 following swathing. Grain moisture at swathing averaged 28% wet basis. Standing grain in the same check was direct harvested from 305 m (1000 ft) long sections on days 5 and 18 following swathing of the twelve windrows. Standing grain moisture on day 5 was 26%, and on day 18, 16.6%. Spike tooth harvesters were used to harvest both the windrows and the standing grain. A cylinder speed of 775 rpm and cylinder clearance setting of 2 on a Deere 7700 combine were used up to day 6 on the windrow harvest and on both harvests of standing grain. At day 8, the cylinder speed was dropped to 600 rpm for the windrow harvest to reduce damage associated with the low moisture levels (<14%) attained by that date.

Cutter bar height on the swather was set at approximately 430 mm (17 inches). Due to increased soil moisture at the time of swathing compared to the 1986 field trial, with concommitant loss to the tracks on the swather, the chopper was able to recover only a total of 480 g/m (0.3 lb/ft) dry basis across the full windrow, rather than the 700 to 1100 g/m (0.47 to 0.74 lb/ft) of the 1986 trial. The bulk density of the chopped stubble was measured at 13 kg/m^3 (0.81 lb/ft^3). The total depth of cover was 26 mm (1 inch), and was observed to be lighter than the cover obtained during the trial of the previous year. The loss of stubble in the tracks of the swather is the primary incentive for developing a covering system mounted on the swather.

Sections of both open and covered windrows were collected at the end of the trial and threshed with a plot thresher. The grain fraction of the total mass for the open windrows was 0.69, compared to a grain fraction of 0.63 for the covered windrows. The grain to non-grain ratio was thus 2.18 for the open windrows compared to 1.70 for the covered windrows.

A weather station was located in the check to record environmental data. Air temperature, relative humidity, wind speed and wind direction were recorded at 2 m (6.6 ft) and 0.5 m (1.6 ft) elevation, the latter corresponding to the top of the windrow. Also recorded were solar radiation, temperatures at seven locations throughout the open and covered windrows and in the soil beneath the windrows, and the presence of dew (this indicator provided only a measure of whether condensation had formed, not the quantity of condensation over an interval). The seven thermocouples were placed to record the temperature of the interior of a cut stem on the surface of the covered and open windrows, the temperature of the lower surface of the windrows, the temperature under the stubble and at the level of the grain in the covered windrows, and the temperature of the soil immediately beneath the windrows. The dew sensor was initially placed on the surface of an open windrow. On day 12 it was moved to beneath the stubble cover on a covered windrow. On day 17 it was again directly exposed. All sensors were sampled at 60 second intervals with ensemble averages recorded at 15 minute intervals over the duration of the test.

Windrow sections of 2.2 m^2 (24 ft^2) within an open and a covered windrow were suspended on load cells to record weight changes of the windrows over time. These load cells were sampled at 15 minute intervals over the duration of the trial. Drying rate data could be obtained, as well as a quantitative estimate of the condensation and adsorption of moisture by the windrow over the course of the night (and during any precipitation that may have ocurred).

Ten samples of grain were collected from the grain auger in the grain tank of the harvester during the harvest of each windrow or section. Each sample of approximately 2000 g (4 lb) was collected over a 30 m (100 ft) interval as the harvest progressed. Time to complete the harvest of each windrow was recorded. Samples were immediately placed in an insulated container. Grain from each windrow was conveyed to a tared bankout wagon and weighed. Harvesting began at 11:00 a.m. with each day's test normally complete by noon including all data acquisition. Harvesting of a single windrow typically required about 5 minutes.

On October 6, all windrows were rethreshed (cylinder speed 950 rpm, no clearance) to estimate threshing loss. All grain from each windrow was collected in bags at the grain auger in the tank, weighed, and sampled for moisture. Single samples were also collected for milling evaluation, although these were intended to be informative only because of the high cylinder speed. Qualitative estimates of shatter loss were made by inspecting the area under the windrow after threshing.

Samples were returned to the laboratory for ambient air drying to 12 - 13% in preparation for milling evaluations. For samples initially at moisture contents less than 14%, samples were ventilated with ambient air for a period of up to an hour for cooling to room temperature. No attempt was made to rehydrate samples initially lower than 13% because of the anticipated damage associated with adsorption of moisture by the grain, even though the moisture content at milling is known to have an influence on the head rice yield obtained (Pominski, et al., 1961). The increase in head rice with reduced moisture content at milling is more important for long grain varieties than for medium grain varities. Over the range considered, the uncertainty associated with the different moistures at milling was preferred to the uncertainty associated with the rehydration of the grain. Prior to drying or ventilating, subsamples were collected for moisture analysis using a drying oven. Following drying, primary samples were bagged, sealed, and stored for a minimum period of two weeks. Milling evaluations were conducted by the California Department of Food and Agriculture Grain Inspection Station (Sacramento, CA). These evaluations included moisture content at milling, total milled rice yield fraction, head rice fraction, dockage fraction, and grade.

Over the course of the trial, samples of straw and stubble were collected and analyzed for moisture. Stubble from the covered windrows was collected just prior to threshing. Straw samples were collected from the windrow immediately after threshing. Samples of the stubble supporting the windrows were also taken. Samples of the straw from the standing grain sections were taken immediately after cutting and threshing.

Results of 1987 Field Trial:

Head rice yields from the covered and open windrows, as well as the standing grain, are shown in Fig. 7. The open windrows show a precipitous drop over the first six days following swathing, decreasing from nearly 65% whole kernel to 37% whole kernel yield over the interval. Grain quality from the covered windrows shows a lower rate of decline over the same period, obtaining 47% whole kernel yield after six days. Both treatments show an increase in head rice yield at day 8. This is due to the reduction in cylinder speed to accomodate the lower moisture content. This reduction in cylinder speed should probably have been done prior to harvest at day 3. Following this adjustment, the open windrows show a continuing decline at an accelerating rate, while the covered windrows demonstrate a continuing decline, but at a decelerating rate. The standing grain harvested on day 5 also shows a head rice of about 65%, which would be expected because of the high moisture content of 26%. By day 18, when the standing grain achieved a moisture of 16.6%, the head rice yield had dropped to 42%, actually somewhat lower (but not significantly at the 95% level) than the head rice yield of the grain in the covered windrows harvested one day earlier, but at a moisture content of 10%. The head rice yield of the standing grain at day 18 might have been higher had the cylinder speed been decreased to accomodate the reduced moisture of the grain. Threshing loss data would support this, but the extent of loss resulting from such a decrease is not known. The head rice yield of the grain in the covered windrows after 3 days was 58%, even though the grain moisture had dropped to less than 14% and the cylinder speed was 775 rpm.

Grain dryed rapidly in both types of windrows, coming into equilibrium at about day 3 (Fig. 8). The weather during the first three days of the trial was characterized by very warm daytime air temperatures (Fig. 9). The suceeding three days were somewhat cooler, followed by a return to warm days for the duration of the trial. Air relative humidity at 0.5 m (1.6 ft) elevation (Fig. 9) dropped to low levels (~10%) during the days, reaching 100% at night during the first day, and reaching at least 95% each night thereafter. Humidities decreased in general as the soil dried. Dew was observed on the surface of the windrows each night throughout the trials as indicated in Fig. 10 (from day 12 to 17 the dew sensor was located under the stubble cover and was not observed to be wetted). Dew was visually observed not to penetrate the stubble cover, but to form only on the upper surface of the windrows. Dew formation and moisture adsorption by the straw and the grain were observed by weight changes monitored on the load cells (Fig. 11). The rapid drying during the first three days is readily seen, as are the diurnal cycles of wetting and drying, in Fig. 11, where the residual mass fraction (remaining mass on load cells divided by initial mass at the start of the trial) is plotted as a function of time. The covered windrows have a somewhat lower residual mass fraction than the open windrows because of the higher straw to grain ratio and the higher initial moisture content of the straw compared to grain (compare Fig 12 and Fig. 8). The equilibrium conditions of the windrows from days 3 to 8 and from days 8 to 17 can also be seen in Fig. 11. The final values on day 17 correspond to grain moistures of 10% and straw moistures of 6%.

Surface temperatures on the open windrows generally exceeded the temperatures under the stubble cover of the treated windrows by 5 to 7°C (9 to 13°F) as shown by Fig. 13. More important is the difference in temperature at night, where the surface temperature of the windrows is observed to drop below the dew point of the air at that level on every night, whereas the temperature under the stubble cover is seldom observed below the dew point. Fig. 14 contains the data obtained on the night of day 10 for temperatures of the soil, air, windrow surface, and under the stubble cover compared to the dew point temperature. This is typical of the entire trial. Shortly after sunset, the windrow surface temperature drops below the dew point and condensation is observed to form on the surface. Such condensation was not visually observed under the stubble cover, and the temperature data supports this observation. Grain exposed on the surface of the windrow would be subject to rewetting by both moisture adsorption and condensation. Grain in the treated windrows would be subject to rewetting by adsorption, but less subject to rewetting by direct condensation.

Data obtained on the physical process of harvesting are included in Figs. 15 - 19. Measured forward velocities of the harvester are shown in Fig. 15. Velocity increases during the first 8 days, reaching a constant value after day 8. Much of the initial variation is thought to be due to the effect of the sampling operation on the harvester operator, such that speeds normally obtained during swath harvesting were not obtained during the experiment, although no direct constraints on the operator were made during harvesting. This is also thought to be true for the period after day 8, when the velocity was observed to be less than that of similar harvesters working in windrows not associated with the experiment. The higher speeds when harvesting standing grain are associated with the fact that the sections of standing grain harvested were somewhat less than a full standard header width. When the harvester capacities are compared (Fig. 16), the differences between the swath and direct harvesting operations are seen to largely vanish. There is also not a clear distinction between open and covered windrows in harvester capacity.

The total harvestable yield of grain for each windrow is shown in Fig. 17. These values have been normalized to include the threshing loss and remove the dockage. Field uniformity was reasonably good, with some variations in the windrows harvested on days 3 and 17.

Loss data obtained by rethreshing the windrows is shown in Fig. 18. The very high loss values occurring on days 1 and 17 are due to improper pickup header operation by the harvester operator. A substantial amount of unthreshed grain was left in the windrow, apparently because the pickup header was not set low enough to recover this grain. It was readily recovered by the same header during the rethreshing operation, however, so can only be attributed to operator oversight. The data for the other days does not show a substantial difference between the threshing loss for the open windrows and the standing grain, but there is a trend to somewhat higher loss for the covered windrows compared to the open windrows. This is most likely due to the lower grain to non-grain ratio for the covered windrows. This loss might potentially be offset by increasing the cylinder speed slightly in the covered windrows, although this could lead to increased grain breakage and reduced head rice yields. The loss measured does not appear to be exceptionally high in any case. Visual inspection of the area beneath the windrows showed some trend to increased shatter loss with continued exposure in the windrows, primarily beginning after day 6. Shatter loss may be associated with the lower grain yields found on day 17, but this portion of the check was visually observed to have a lower plant density as well. Shatter loss would not be associated with the reduced yield for day 3. The grain yield obtained on this check was not significantly different than the yield obtained by the grower on other checks in the same area. The low value of loss occurring in the standing grain on day 18 implies that the cylinder speed could have been slowed, possibly increasing the head rice yield. Separation in the threshing cylinder appears to occur more readily at lower moisture contents, and cylinder speeds may be reduced accordingly.

Dockage values are included in Fig. 19. Dockage averaged in all cases less than 1%, and was not consistently higher for the covered windrows compared to the open windrows as might be expected from the results of the similar trial of 1986. Better operation of the harvester during the 1987 trial might account for some of the variation. All the grain harvested was graded U.S. No. 1.

Economic Comparison of Direct and Swath Harvesting Techniques

Three major costs are incurred past the maturation date of the grain. These are the harvesting, transportation, and drying costs. Under the assumption that production costs up to the maturation date are similar, the reduction in net value of the grain may be compared for direct and swath harvesting techniques on the basis of the magnitudes of these three cost categories. The total grain value is dictated by the quality of the grain (head rice yield) and may be expressed in terms of the total fraction of milled rice, the fraction of whole kernels, and the prices paid for whole and broken kernels (see Table 1 for nomenclature):

$$z_v = y_h p_h + (y_t - y_h) p_b \qquad [1]$$

In this analysis, all costs and revenues are normalized to zero moisture content for direct comparison among alternatives. Integrated over any season, the net value of grain harvested is found as

$$Z = Z_v - Z_h - Z_t - Z_d \qquad [2]$$

where the subscripts v, h, t, and d denote the revenue received from the sale of grain, and the costs of harvesting, transportation, and drying respectively. For both methods, the value of Z for any harvested area A may be computed and compared to determine the preferred technique under the given constraints and conditions. An analytical solution for Z may be found under the following assumptions:

1. Appropriate models may be formulated describing the status (quality and moisture) of the grain as a function of time, and
2. The time discreet nature of the harvesting operation may be resolved as a continuous problem without introducing substantial error into the analysis.

Subsequent comparison with experimentally determined values has shown these two assumptions to be reasonable.

Direct Harvesting:

<u>Value of the grain:</u>
On a daily averaged basis, the total grain value over the season, Z_V, is

$$Z_v = \sum_{t_s}^{t_f} G(y_h p_h + (y_t - y_h) p_b) \qquad [3]$$

where the daily grain production function, G, is

$$G = 3600\, h\, Y\, (1-y_l)\, n_h\, v_h\, w_h\, \eta_h \qquad [4]$$

and the summation is taken from the start of harvest, t_S, to the end of harvest, t_f, with

$$t_f - t_s = \frac{A\,Y\,(1-y_l)}{G} \qquad [5]$$

Under assumption 2. above, equation [3] may be reformulated as

$$Z_v = \int_{t_s}^{t_f} G(y_h p_h + (y_t - y_h) p_b)\,dt \qquad [6]$$

The term y_h changes with time, and is found to depend largely on the moisture content of the grain at harvest, assuming that the harvester has been properly adjusted for cylinder speed and clearance. The moisture content is also a time dependent function and generally estimated through the use of stochastic models incorporating weather and crop variables. Over relatively short time intervals in good weather, the drying of the standing grain may be approximated by an exponential decay in moisture, such that

$$m = m_f + (m_o - m_f)\, e^{-\frac{t}{\tau_d}} \qquad [7]$$

The final moisture, m_f, is taken as the equilibrium moisture for the prescribed daily averaged temperature and relative humidity, while m_o is assumed equal to the moisture at maturation. The time constant, τ_d, is distinguished from that used to estimate the moisture content of the grain in the swath, τ_w, introduced later. The head rice yield is assumed to decline linearly with moisture with the exception that over the moisture interval $m_o \geq m \geq m_{h,o}$, the head rice yield is assumed constant at the intial value at maturation, $y_{h,o}$.

$$y_h = y_{h,o} - r\,(m_{h,o} - m) \qquad [8]$$

This is in keeping with experimental data obtained during this study and is also consistent with data presented by Luh (1980). The linear dependence of head rice yield on moisture is not valid after the grain has come into equilibrium. Continued exposure with similar ambient conditions will result in declining head rice yields because of the cyclic rewetting of the grain in the panicle due to adsorption and condensation (dew). Over the interval of interest here, however, this appears to represent a reasonable, if somewhat conservative, estimate of head rice yield during direct harvest. The temporal variability in head rice yield is then achieved through the time dependence of moisture expressed by equation [7].

Equation [6] can now be integrated with the further assumptions that G and y_t are independent of moisture, and hence constant in time:

$$Z_v = G\left[\int_{t_s}^{t_{h,o}} (y_{h,o}\, p_h + (y_t - y_{h,o}) p_b)\,dt + \int_{t_{h,o}}^{t_f} (y_h p_h + (y_t - y_h) p_b)\,dt\right] \qquad [9]$$

$$= Z_1 + Z_2$$

$$Z_1 = G(y_{h,o}p_h + (y_t - y_{h,o})p_b)(t_{h,o} - t_s) \quad [10]$$

$$t_s = -\tau_d \ln\left[\frac{m_s - m_f}{m_o - m_f}\right] \quad [11]$$

$$t_{h,o} = -\tau_d \ln\left[\frac{m_{h,o} - m_f}{m_o - m_f}\right] \quad [12]$$

$$Z_2 = G\left[c_1(t_f - t_{h,o}) + c_2\tau_d(e^{-\frac{t_{h,o}}{\tau_d}} - e^{-\frac{t_f}{\tau_d}})\right] \quad [13]$$

$$c_1 = (p_h - p_b)(\alpha + r\, m_f) + p_b y_t \quad [14]$$

$$c_2 = r(m_o - m_f)(p_h - p_b) \quad [15]$$

$$\alpha = y_{h,o} - r\, m_{h,o} \quad [16]$$

The starting moisture content, m_s, used to find t_s may be an imposed upper limit, such as that frequently set by the receiving dryer to maintain dryer capacity.

Harvesting Cost:

The harvesting cost is the sum of the fixed and variable costs of operating the harvester and the bankouts. Because the cost of operating the bankouts is similar for both direct and swath harvesting, only the cost of the harvester operation is considered here.

The fixed costs are computed on an annual basis from the capital cost of the harvester, the interest rate on capital, and the financial and technical lives of the harvester. The variable costs include the cost of fuel, labor, and maintenance for the harvester. The annual fixed cost allocated to the rice harvesting operation may be adjusted by the inclusion of an allocation factor, ξ, in the event that the harvester is used for other crops during the year, or multiple harvests of area A occur during the season. The latter is more likely with large farms with several plantings throughout the season. The allocation factor is used to test the effect of scale, or size of farm, on the cost of harvesting.

The cost of harvesting is then expressed as

$$Z_h = n_h \left[\frac{\phi C}{\xi} + \int_{t_s}^{t_f} c_h h \, dt \right] \quad [17]$$

$$= n_h \left[\frac{\phi C}{\xi} + c_h h (t_f - t_s) \right]$$

$$\phi = \frac{i(1+i)^n}{(1+i)^n - 1} \quad [18]$$

The cost of capital is considered only throughout the financial life of the harvester. If the technical life extends beyond the financial life, no further capital recovery charge is required. The variable costs would be expected to increase with time due to increased maintenance requirements, offsetting the discharge of capital costs. This type of variation over the life of the harvester is not considered further here, and the analysis is completed on a first year basis. In the event that the harvesting operation is contracted, then the annual harvesting cost is readily computed from the contract price, which is normally asssigned per unit mass of grain harvested.

<u>Transportation Cost:</u>

The transportation cost is also a function of the moisture content of the grain. Because trucks are normally weight limited rather than volume limited, any reduction in moisture serves to increase the payload of dry grain (zero moisture basis) carried on a truck during each trip. The transportation cost is determined as:

$$Z_t = G \int_{t_s}^{t_f} \frac{p_t d}{1 - m} dt = G p_t d \int_{t_s}^{t_f} \frac{1}{1 - m} dt \qquad [19]$$

Equation [19] may be integrated by noting

$$dt = \frac{-\tau_d}{m - m_f} dm \qquad [20]$$

Upon substitution, equation [19] becomes

$$Z_t = - G p_t d \int_{m_s}^{m_{t_f}} \frac{\tau_d}{(1 - m)(m - m_f)} dm \qquad [21]$$

$$= \frac{G p_t d \tau_d}{1 - m_f} \left[\ln \frac{(m_s - m_f)(1 - m_{t_f})}{(m_{t_f} - m_f)(1 - m_s)} \right]$$

where the moisture at $t = t_f$ is given by equation [7].

Drying Cost:

The cost associated with drying is composed of handling charges as well as energy costs. Rice delivered to the dryer at or below $m = 0.14$ will still incur a handling charge even though it technically does not require further drying. For $m > 0.14$, the drying charge increases substantially. A recent drying schedule (Farmer's Rice Cooperative, 1986) is divided into four regions, with cost increasing linearly between moisture limits in all but the first region ($m \leq 0.14$), where the cost is constant. The other divisions occur at m = 0.25 and m = 0.28. For this analysis, an approximation using the form of the energy cost function was found to adequately model the published drying schedule without discontinuities appearing above m=0.14. For drying between initial moisture content, m, and final moisture content, $m_{d,f}$, the mass of water evaporated per unit mass of dry grain is

$$m_e = \frac{m - m_{d,f}}{(1 - m)(1 - m_{d,f})} \qquad [22]$$

The drying cost is therefore related in form to equation [22], and is approximated by

$$Z_d = G \int_{t_s}^{t_f} \left[\beta \left(\frac{m - m_{d,f}}{1 - m} \right) + \gamma \right] dt \quad , \quad m > m_{d,f} \qquad [23]$$

$$= G\,\gamma_d \int_{t_s}^{t_f} dt \quad , \quad m \leq m_{d,f} \qquad [24]$$

When $m \leq m_{d,f}$, the drying cost is constant for all rice delivered. Equation [23] may be integrated by setting $m_f = m_{d,f}$ and substituting dt from equation [20] to yield:

$$Z_d = G \left[-\beta \tau_d \int_{m_s}^{m_{t_f}} \frac{1}{1 - m} dm + \gamma \int_{t_s}^{t_f} dt \right] \qquad [25]$$

$$= G \left[\beta \tau_d \ln \left(\frac{1 - m_{t_f}}{1 - m_s} \right) + \gamma (t_f - t_s) \right]$$

Swath Harvesting:

Value of the grain:

The solution for the total grain value is complicated by the generation of delays in the swathing operation resulting from a reduced drying time in the windrow required to attain the desired harvest moisture content. In general the swather has a far greater capacity than a single harvester, and if serving only one harvester need only work a reduced number of hours each day. As the harvest continues and the moisture content of the standing grain declines, the number of days needed to reach the harvest moisture or below will also decline, until at some point the swather can delay a day while the harvester continues to operate. This has no effect on the equipment costs, but will change the head rice yield of the grain, and thus the value of the grain. The time at which a delay is generated depends upon the drying rate of the grain in the windrow, here also modeled as an exponential decay of the form

$$m_w = m_{w,f} + (m_{w,o} - m_{w,f})\, e^{-\frac{t}{\tau_w}} \qquad [26]$$

When the value of t in equation [26] is reduced by 1 day in drying from the initial moisture content in the windrow, $m_{w,o}$, to the harvest moisture, $m_w = m_{w,h}$, the swather is delayed. This implies that grain swathed at intermediate values of t will reach moisture contents lower than $m_{w,h}$, but this should not affect the head rice yield as there is not an additional cycle of rewetting.

The reduction in head rice yield of the grain in the windrow is taken as a direct function of time spent in the windrow, t_w, because of the apparent dependence on the number of cycles of rewetting the grain endures:

$$y_{h,w} = y_{h,w,o} - r_w\, t_w \qquad [27]$$

The initial head rice yield of the grain in the windrow, $y_{h,w,o}$, is the head rice yield of the grain at the time of swathing, and varies in accordance with the assumptions described under direct harvest.

The solution for the total grain value is found in a similar manner as discussed earlier. Modifications are made to account for the changes in head rice while in the windrow and the changes in head rice in the standing grain prior to swathing, including any delays. The integration is done over multiple time periods starting with t_o, the time of maturation, and proceeding through $t_{h,o}$, the time at which the head rice yield on the standing grain begins to decline; $t_{\delta 1}$, the time of the first swather delay; $t_{\delta 2}$, the time of the second swather delay; and continuing through each delay introduced. The order of integration depends on knowledge of the specific conditions of the harvest. The resultant solution with the order just described is:

$$Z_v = G\left[(p_h - p_b)(y_{h,o} - r_w t_w) + p_b y_t\right](t_{h,o} - t_o) \qquad [28]$$

$$+ G\left[c_1' (t_{\delta 1} - t_{h,o}) + c_2 \tau_d \left(e^{-\frac{t_{h,o}}{\tau_d}} - e^{-\frac{t_{\delta 1}}{\tau_d}} \right)\right] + \ldots$$

$$+ G\left[c_1' (t_{f,w} - t_{\delta n}) + c_2 \tau_d \left(e^{-\frac{t_{\delta n}}{\tau_d}} - e^{-\frac{t_{f,w}}{\tau_d}} \right)\right]$$

$$c_1' = (p_h - p_b)(\alpha + r\, m_f - r_w t_w) + p_b y_t \qquad [29]$$

$$G = 3600\, h_w\, Y\, (1 - y_l)\, n_{h,w}\, v_{h,w}\, w_s\, \eta_{h,w} \qquad [30]$$

and t_w is the appropriate value from equation [26]. The width of the swather, w_s, is used in computing the daily grain production function, G, for the windrow harvester. The operating time of the swather relative to the number of harvesters being served is:

$$h_s = h \left[\frac{n_{h,w}}{n_s} \frac{v_{h,w}}{v_s} \frac{\eta_{h,w}}{\eta_s} \right] \qquad [31]$$

and the total number of operating days for the swathers and the harvesters is:

$$t_n = \frac{A}{n_s\, h_s\, v_s\, w_s\, \eta_s} \qquad [32]$$

Harvesting Cost:

The cost of harvesting is similar to that derived for direct harvesting with the addition of the swather cost.

$$Z_h = n_{h,w} \left[c_{h,w}\, h_w\, t_n + \frac{\phi_{h,w}\, C_{h,w}}{\xi} \right] + n_s \left[c_s\, h_s\, t_n + \frac{\phi_s\, C_s}{\xi_s} \right] \qquad [33]$$

Transportation Cost:

The estimate of transportation cost may be simplified if the windrow harvested grain is harvested at approximately the same moisture content on each day. Under this assumption, the transportation cost is:

$$Z_t = A\, Y\, (1 - y_l) \frac{p_t\, d}{1 - m_{w,h}} \qquad [34]$$

Drying Cost:

The drying cost may also be simplified if harvesting is done with $m_{w,h} = m_{d,f}$, and only handling charges are incurred. This in fact yields a conservative estimate of the net grain value as it tends to sacrifice head rice yield for reduced moisture, while the marginal revenue due to quality is greater than the marginal cost of drying. Under this assumption, the drying (handling) cost is:

$$Z_d = A\,Y\,(1 - y_l)\,\gamma_d \qquad [35]$$

If the assumption $m_{w,h} > m_{d,f}$ is made instead, the drying cost is:

$$Z_d = A\,Y\,(1 - y_l)\left[\beta\left(\frac{m_{w,h} - m_{d,f}}{1 - m_{w,h}}\right) + \gamma\right] \qquad [36]$$

Results of the Economic Model:

The model just described was used to evaluate the economic feasibility of swath harvesting in comparison to direct harvesting. Values of the prescribed physical and economic parameters are listed in Table 2. Values for p_h and p_b were derived from published rate schedules for the 1987 loan agreements. Coefficients used to determine the drying costs were derived using published drying schedules (Farmer's Rice Cooperative, 1986). Other economic parameters were developed based on information supplied by growers. The physical parameters influencing the grain status were derived from experimental data discussed earlier. Parameters describing equipment function were based on experimental data collected during this study and on observations of a large commercial operation currently engaged in swath harvesting for a part of the crop, but with open windrows. The value assumed for A is largely arbitrary, and is intended to represent the size of a block coming into maturity at any one time. Harvesting costs assume grower owned equipment with full financial burden. These costs are found not to be substantially different than current contract rates of harvesting which might more typically be applied to smaller farms.

Categorical comparison of direct and swath harvesting:

Magnitudes of costs and revenues for each category are shown in Fig. 20. These costs and revenues were computed using what will be referred to as the "base case" assumptions. The starting moisture content for the direct harvest is assumed to be 24.5%, given as an imposed limit by the dryer. The swath harvest is assumed to start at maturation with a 30% grain moisture content and use the modified technique. An allocation factor $\xi = 5$ is assumed for all equipment. In each case, there is a single harvester operating over an eleven day period for the direct harvest and a twelve day period for the swath harvest to finish the harvest on 10^6 m^2 (250 acres). The swath harvesting operation includes one swather operating 2.2 $h \cdot d^{-1}$ with one delay generated at day 6. The swath harvesting takes approximately one operating day longer than the direct harvest because of the assumed lower field efficiency and the shorter header width assigned to the swather. This results in the swath harvesting operation finishing 12 days after maturity, while the direct harvest operation must wait 4 days to begin, finishing 15 days after maturity. The moisture content of the grain at the end of direct harvesting is 17.6%. All grain delivered under the swath harvesting operation is less than 14% moisture. The grain remains in the windrow for three days up to day 6, after which it remains two days. These results are consistent with the experimental data of 1987, when the harvest took place earlier in the season. The time constant for drying in the windrow should be extended later in the season as the drying rate slows, as was shown with the 1986 experiments.

The results of the base case analysis show the value of the grain, Z_V, harvested under the swathing operation to be slighty greater than that of the direct harvesting operation by a small amount of 0.2%. This is due to the slightly greater head rice yield achieved by swathing. The harvesting cost is increased by 50% as a result of the lower equipment capacity and the added cost of the swather. The transportation cost is reduced 7.5% by swathing. The drying cost is reduced 64% by swathing. The net grain value, Z, is improved a total of 6% by swathing.

The influence of the scale or size of the operation is indicated in Fig. 21. To increase the apparent scale, the allocation factor, ξ, is adjusted upwards. The limit on how large ξ can be is given by the length of the season, which in general is taken at about 60 days. For this case, the limit on ξ is about 5, implying five consecutive harvests over a total area of 5×10^6 m^2 (1250 acres). As the scale increases beyond this, additional harvesters must be brought in to finish the harvest in the indicated time. This is also true if the harvests of individual blocks begin to overlap, and in this case, the value of ξ would be adjusted downwards. Fig. 21 shows that as the scale increases, the advantage to swathing increases, whereas at the lowest scale, $\xi = 1$, the direct harvesting operation has a slight advantage compared to swathing. If the financial burden of the equipment has been met, as might be the case with older harvesters, the advantages of direct harvesting under the base case assumptions vanish, unless the operating costs of the swather are increased substantially.

Optimization of the harvesting operation:

The solution obtained above indicates that the harvesting operation may be optimized under the assumptions made. In particular, the number of harvesters and the initial moisture content for direct harvest may be optimized. Fig. 22 includes the results of the model with variable initial moisture and variable number of harvesters for the direct harvesting analysis. All other factors have been held constant, with $\xi = 5$. With only one harvester, the optimum approach is to begin harvesting as early as possible (immediately past maturity) as the increased head rice yields will offset the increased drying costs. Unfortunately, the imposed upper limit on moisture in the grain delivered to the dryer may require starting the harvest at lower moistures than optimal. At moistures less than 27% and above 21%, the model indicates two harvesters are preferred, with the increased head rice yields resulting from the faster harvest offsetting the additional financial cost of another harvester. Below 21%, the added financial cost cannot compensate for the loss in value due to the rate of decline in head rice, and a single harvester is again preferred. For the value of A assumed, the model does not indicate that three harvesters would be of benefit. The relative improvement in the net grain value as additional harvesters are added at any given initial moisture is shown in Fig. 23.

Fig. 24 illustrates that the rate of decline of head rice over time in the windrow can also influence the optimal number of harvesters to use in the case of swath harvesting. Two values are included: no decline (typical of the 1986 experiment), and a decline of 2 points of head rice per day (r_W = 0.02) of exposure (typical of the 1987 experiment up to 3 days exposure, possibly longer with proper settings for cylinder speed and clearance). One harvester is sufficient with the higher rate of decline, whereas two harvesters result in an improved profit if there is no decline in head rice yield in the windrow. The net grain value actually decreases linearly with increasing rates of decline as shown in Fig. 25 because of the linear nature of the pricing schedules (equation [1]). Fig. 25 also indicates the advantage in using the modified swathing technique relative to open windrows if the swathing cost is not substantially altered by the equipment needed to treat the windrows.

Discussion

The relationship between head rice yield and moisture content for the standing grain assumed in the economic model obviously cannot be maintained as the grain comes into equilibrium at m_f. Experimental data (Luh, 1980, Battacharya, 1980) suggests that the head rice yield continues to decline much in the same manner as assumed here for the grain in the windrows. Accounting for this effect in the model would tend to decrease the net grain value computed for the direct harvesting operation.

In addition, the grain often goes through a period of relatively constant high moisture which generates delays in the direct harvesting operation. During maturation the grain apparently first goes through a period of physiological moisture decrease as the dry weight increases, then stays at a moisture content of about 28% for ten days, followed by a physical moisture decrease under the influence of weather (Kunze, 1977). Fissuring and cracking of the grain is found to occur during this latter period, with kernels above 20% moisture not subject to cracking by wetting. The range in moisture content among grains on an individual panicle may be about 10%, implying that grain harvested at moistures below 25% might include increasing proportions of fissured grains (McDonald, 1967; Kunze, 1977), although the moisture range depends in part on the variety of grain, and was found by Chau and Kunze (1982) to be higher than 10% for wetter panicles and less than 10% for dryer panicles. The period of constant, but high moisture causes delays in the direct harvesting operation when the grain received at the dryer is under an imposed moisture limitation. This is not the case with the swath harvesting operation. The rice conceivably could be swathed at any time during and after this period, given appropriate weather conditions. Were the delay to last ten days, the swath harvest could be virtually finished while the direct harvest was just beginning for the base case assumptions of the model. For growers with larger plantings of rice, the resultant increase in apparent season length should allow better utilization of harvesting equipment, possibly reducing the number of harvesters required during peak times. This would tend to decrease the cost of swath harvesting relative to direct harvesting.

The effect of rain on the grain in the covered windrows has not been fully evaluated. The light rain during the 1986 trial had no apparent effect on the grain quality in the treated windrows. The moisture content was actually somewhat lower than that of the grain in the open windrows at harvest on the following day. The effect was perhaps similar to a heavy dew. Soaking rains could lead to increased damage due to wetting of the grain and losses from the attempted harvest of damp windrows. If followed by relatively good weather, the rate of grain drying should be similar to that of the open windrows. Soil drying should also be improved, resulting in earlier entry into the field compared to a standing crop. The effect of rain is clearly a limitation to the swath harvesting system, even in modified form, and the flexibility to change headers on the harvesters should be maintained. The application of the method later in the season when the probability of rainfall is higher requires further investigation.

The substantially lighter coverage of the windrows in 1987 compared to the 1986 and 1985 trials still resulted in significant improvements in head rice compared to open windrows. A formal mechanism for the damage occuring in the windrows has not yet been elucidated, but the difference in the exposure levels to rewetting is postulated to be the major influence. Grain in the open windrows, and for that matter, the standing crop, is subject to rewetting from two sources (excluding precipitation): 1. adsorption as the grain attempts to comes into equilibrium with the surrounding atmosphere, and 2. direct exposure to condensation (dew). The experimental data (see, for example, Fig. 14) clearly indicates that the covered windrows, even with a light cover, have lower exposure to condensation, and rewetting occurs primarily by adsorption. The apparent leveling in head rice yields from the covered windrows towards the end of the 1987 trial (Fig. 7) could be due to the reduction in adsorption moisture changes as the soil and straw dried and the relative humidity of the surrounding atmosphere declined (Fig. 9). The accelerated decline in head rice from the open windrows over the same time is consistent with condensation rewetting of grain which had dropped below the critical moisture content (particularly after day 8). The trial of 1986 suggests a similar conclusion, although the variety of rice may have been less susceptible to fissuring. M9 is known also to be a variety which is harder to thresh, and some of the changes may have been masked by the higher cylinder speed required to harvest the grain, in addition to the cooler weather prevailing during this trial. The 1985 trials were not extended long enough to observe an effect similar to that of the 1987 trial, although the results are very similar to the first four days of the 1987 trial. Dew on the surface of the windrow would certainly influence the humidity under the cover, but the quantity of dew formed on the surface declined over the 1987 trial as the field dried, and the effect on the grain under the cover would have been reduced as the trial progressed. Lower temperatures and slower drying rates compared to grain on the surface of the windrow might also have had some effect.

As a means of drying the grain in the field, the modified swathing technique is certainly preferable to leaving the grain on the standing crop. The standing grain harvested on day 18 of the 1987 trial had a moisture content of 16.6% and a head rice yield of 42%. After two days in the covered windrow, the grain moisture had dropped to 18% (5 points drop per day) with a head rice yield of 62%.

Mixing of wet and dry rice has been shown to lead to fissuring and cracking of the drier kernels (Kunze and Prasad, 1978). Some concern might therefore exist for swathing the rice and covering with a high moisture stubble. When swathed at high moisture, however, no reduction in head rice is seen over the first day in the windrow (Fig 7). This observation suggests that if the rice is swathed at 25 to 30% moisture, most of the kernels are of high enough moisture to remain unaffected by the high moisture environment around them. As the windrows dry through the next few days, the mixing phenomenon could well influence the head rice yield, and might account for some of the more rapid decline during days 2 and 3 seen during the 1985 and1987 trials. This conclusion is further supported by rapid decline in head rice seen during day 2 of the 1985 trial for the windrows folded after one day of open exposure (Fig. 1). After day 2, however, no further decline is observed, indicating that conditions in the windrow had become more uniform, more so perhaps than the windrows folded immediately. However, the effect observed in the 1987 trial is not separable from the effect of moisture adsorption due to high humidities present in the field in general for the experimental data obtained. This effect requires further investigation. If swathing at low moistures and covering with high moisture stubble is shown to have a serious deleterious effect, there might well be an economic advantage to operating multiple harvesters to ensure that the harvest is completed quickly, before the average moisture at swathing can drop much below 25%. Swathing could reduce the loss of head rice associated with mixing of variable moisture grain in trucks and storage prior to drying. Grain placed in the trucks after harvesting from the windrow is of more uniform moisture because of the drying in the field. This uniformity of moisture also implies a greater potential to optimize the control of the harvester cylinder speed, concave clearance, material throughput, and other machine factors known to affect the quality of the grain and the losses incurred during harvesting.

The quantity of stubble available in the field appears adequate to treat each windrow. Even with the loss of stubble to the tracks of the swather, the 1987 data indicates sufficient coverage to realize a marked improvement in head rice compared to the open windrows. The coverage is unlikely to be perfect, and some grain will be left exposed on the surface. As the quantity of stubble available increases, the probability of obtaining a more uniform cover also increases. This suggests the need to incorporate a windrow treatment mechanism on the swather, and such development is underway. The development of such a mechanism also leads to the potential development of total harvest systems or improved post harvest systems for the recovery of the residual plant biomass, which in California is currently burned in the field for disposal. Satisfactory recovery of the straw requires harvest below the waterline on the plant to avoid reinfestation with stem rot sclerotia. Post harvest technologies have suffered from the inability to recover straw and stubble in the tracks of the harvesters and bankouts. When windrowed, the straw may be suitably recovered, without loss to the tracks of vehicles. If done in one operation, the cutter bar on the swather would need to be set below the waterline, perhaps 75 to 150 mm (3 to 6 inches) above ground level. This would increase the stubble available for cover, but would lead to reducing the rate of drying in the windrow as well as reducing the grain to non-grain ratio in the harvester. The extent to which the drying rate could be reduced may be seen in Fig. 2 for the 1985 trial, in which many of the windrows were cut below the waterline. However, the actual rate for covered windrows is likely to be greater than that indicated in Fig. 2 because of the greater surface area of the windrows and the lower quantity of material above the grain in the windrow. Aeration through the windrow from underneath is also thought to influence the drying rate. Whether such aeration would be impeded by swathing at lower levels, when all the field had been swathed at that level, is uncertain. Some advantage would accrue due to the greater rigidity of the supporting stubble when cut shorter. Stubble supporting the windrow has been observed to fail when the swather cuttter bar is set too high, thereby allowing portions of the windrow to settle on the ground. This could lead to losses from the windrow resulting from a failure to pick up these portions, and could also lead to non-uniformity in moisture because of delayed drying.

Conclusions

The modified swath harvesting technique results in improved head rice yields relative to open windrows. Over a 17 day exposure trial in 1987, the modified technique in which windrows were covered with a layer of stubble showed nearly a 20 point improvement in head rice compared to the open windrow treatment. After the same interval, the head rice yields from the modified windrow treatment were not significantly different from the head rice yields of direct harvested grain, being 43% and 42% respectively, even though grain in the windrows was harvested at 10% moisture compared to 16.6% moisture for the standing grain.

Drying rates for grain and straw in the modified windrows are not significantly different than drying rates in the open windrows. After 3 days exposure during the 1987 trial, grain in both types of windrows had reached 14% moisture after being harvested at 28%. Standing grain moisture at day 5 was 26%. Head rice yields at day 3 were 59% for the covered windrows and 48% for the open windrows. Head rice of the standing grain was not observed to change through day 5, remaining at 65%, but had dropped sharply by day 18.

An economic analysis indicates that grower profit may be increased by proper application of the modified swath harvesting technique. A 6% increase in net grain value was computed for the modified swath harvesting technique compared to direct harvest initiated at a 24.5% grain moisture (assuming an dryer imposed moisture limitation). Drying costs were reduced an estimated 64% by swathing, while harvesting costs were increased 50% assuming full financial costs of new equipment.

The modified technique has been demonstrated successfully during periods of good weather with only a single occurence of rain. The feasibility of the technique under more adverse weather conditions when the probability of rainfall is higher requires further evaluation.

Adequate stubble is available to provide sufficient cover for the grain in the windrows. A layer 26 to 52 mm (1 to 2 inches) deep was obtained during the 1986 trial, without full recovery of stubble from the tracks made by the swather. A lighter cover was obtained during the 1987 trial, but was still sufficient to show improved head rice yields relative to open windrows. Development of a windrow treatment mechanism mounted on the swather is underway to reduce the number of machine operations required and to improve the coverage on the windrows.

Further investigations of the mechanisms influencing grain quality in the windrow are required. Head rice yields in the covered windrows may be higher because of reduced exposure to grain rewetting by condensation (dew) forming on the surface of the windrows at night. Grain in the open windrows and the standing crop is exposed to condensation. All treatments are exposed to adsorption of moisture as the humidity changes, although grain in the covered windrows may experience somewhat more uniform conditions than either the open windrows or the standing crop.

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CONCISE GENERAL SUMMARY OF CURRENT YEAR'S RESULTS

A modified swath harvesting technique has been developed for rice in which the windrow is covered with a layer of stubble. Three years of field trials have demonstrated an improvement in head rice yield for grain in windrows treated by this method relative to open windrows. A trial in 1987 extending over 18 days past swathing resulted in head rice yields of 43% at day 17 for grain in treated windrows, 24% at day 17 for grain in open windrows, and 42% at day 18 for direct harvested grain. Respective grain moistures at harvest were 10% for the treated and open windrows, and 16.6% for the direct harvested grain. Drying rates of grain and straw were equivalent for both treated and open windrows, reaching 14% moisture in the grain by day 3 after swathing, with respective head rice yields of 59% for the treated windrows and 48% for the open windrows. Initial head rice yield at swathing was 65%. An economic analysis shows an improvement in profit of approximately 6% for the modified swath harvesting technique compared to direct harvesting initiated at 24.5% moisture in the grain. The improvement in head rice yields for the treated windrows compared to the open windrows is believed to be due to the reduced exposure to condensation (dew) forming at the surface of the windrow.

Table 1. Nomenclature

Symbol	Description	Units SI	Units English
A	Area	m^2	ft^2
C	Capital cost	$	$
G	Daily grain production	$kg\text{-}d^{-1}$	$lb\text{-}d^{-1}$
Y	Harvestable grain yield (zero moisture basis)	$kg\text{-}m^{-2}$	$lb\text{-}ft^{-2}$
Z	Seasonal cost or revenue on area A	$\$\text{-}y^{-1}$	$\$\text{-}y^{-1}$
c	hourly operating cost	$\$\text{-}h^{-1}$	$\$\text{-}h^{-1}$
d	transportation distance	km	mi
h	operating hours per day	$h\text{-}d^{-1}$	$h\text{-}d^{-1}$
i	interest rate on invested capital	y^{-1}	y^{-1}
m	moisture content (wet basis)	---	---
n	number of equipment items, also	---	---
	number of years of life	y	y
p	price of grain, also	$\$\text{-}kg^{-1}$	$\$\text{-}lb^{-1}$
	unit cost of transportation	$\$\text{-}kg^{-1}\text{-}km^{-1}$	$\$\text{-}lb^{-1}\text{-}mi^{-1}$
r	rate of head rice decline, standing grain	---	---
	and rate of head rice decline, windrow	d^{-1}	d^{-1}
t	time	d	d
v	velocity	$m\text{-}s^{-1}$	$ft\text{-}s^{-1}$
w	width	m	ft
y	yield mass fraction	---	---
z	unit cost or revenue	$\$\text{-}kg^{-1}$	$\$\text{-}lb^{-1}$
α	constant defined by equation [16]	---	---
β	coefficient of the drying cost approximation	$\$\text{-}kg^{-1}$	$\$\text{-}lb^{-1}$
γ	coefficient of the drying cost approximation	$\$\text{-}kg^{-1}$	$\$\text{-}lb^{-1}$
δ	time of delay event	d	d
η	field efficiency	---	---
ξ	allocation factor	---	---
τ	time constant	d	d
ϕ	capital recovery factor	---	---

Subscripts

b	broken kernels
d	direct harvest, drying
f	final
h	head rice, harvest, harvester
l	grain loss
n	generalized time index
o	initial
s	start, swather
t	total, transport, time
v	grain value (revenue)
w	windrow

Table 2. Physical and economic parameter values.

Parameter	Value SI	(English)
A	10^6 m^2	(250 acres)
Y	0.80 kg-m^{-2}	(71 cwt/acre)
y_t	0.70	
$y_{h,o}$	0.65	
y_l	0.01	
m_o	0.30	
$m_{h,o}$	0.23	
m_f	0.14	
$m_{d,f}$	0.14	
$m_{w,o}$	0.30	
$m_{w,f}$	0.10	
τ_d	10 d	
τ_w	1.86 d	
r	3.50	
r_w	0.02 d^{-1}	
h	6 d^{-1}	
v_h	1.12 m-s^{-1}	(2.5 mph)
$v_{h,w}$	1.34 m-s^{-1}	(3 mph)
v_s	2.7 m-s^{-1}	(6 mph)
w_h	5.49 m	(18 ft)
w_s	4.88 m	(16 ft)
η_h	0.7	
$\eta_{h,w}$	0.6	
η_s	0.8	
d	10 km	6 mi
β	0.0572 \$-kg^{-1}	(\$2.60/cwt)
γ	0.0132 \$-kg^{-1}	(\$0.60/cwt)
γ_d	0.0064 \$-kg^{-1}	(\$0.29/cwt)
p_h	0.2654 \$-kg^{-1}	(\$12.04/cwt)
p_b	0.14615 \$-kg^{-1}	(\$6.63/cwt)
p_t	0.0001 \$-kg^{-1}-km^{-1}	(\$0.18/ton-mi)
c_h, $c_{h,w}$	22.75 \$-h^{-1}	
c_s	16.50 \$-h^{-1}	
C, $C_{h,w}$	100 000 \$	
C_s	55 000 \$	
i	0.10 y^{-1}	
n	10 y	

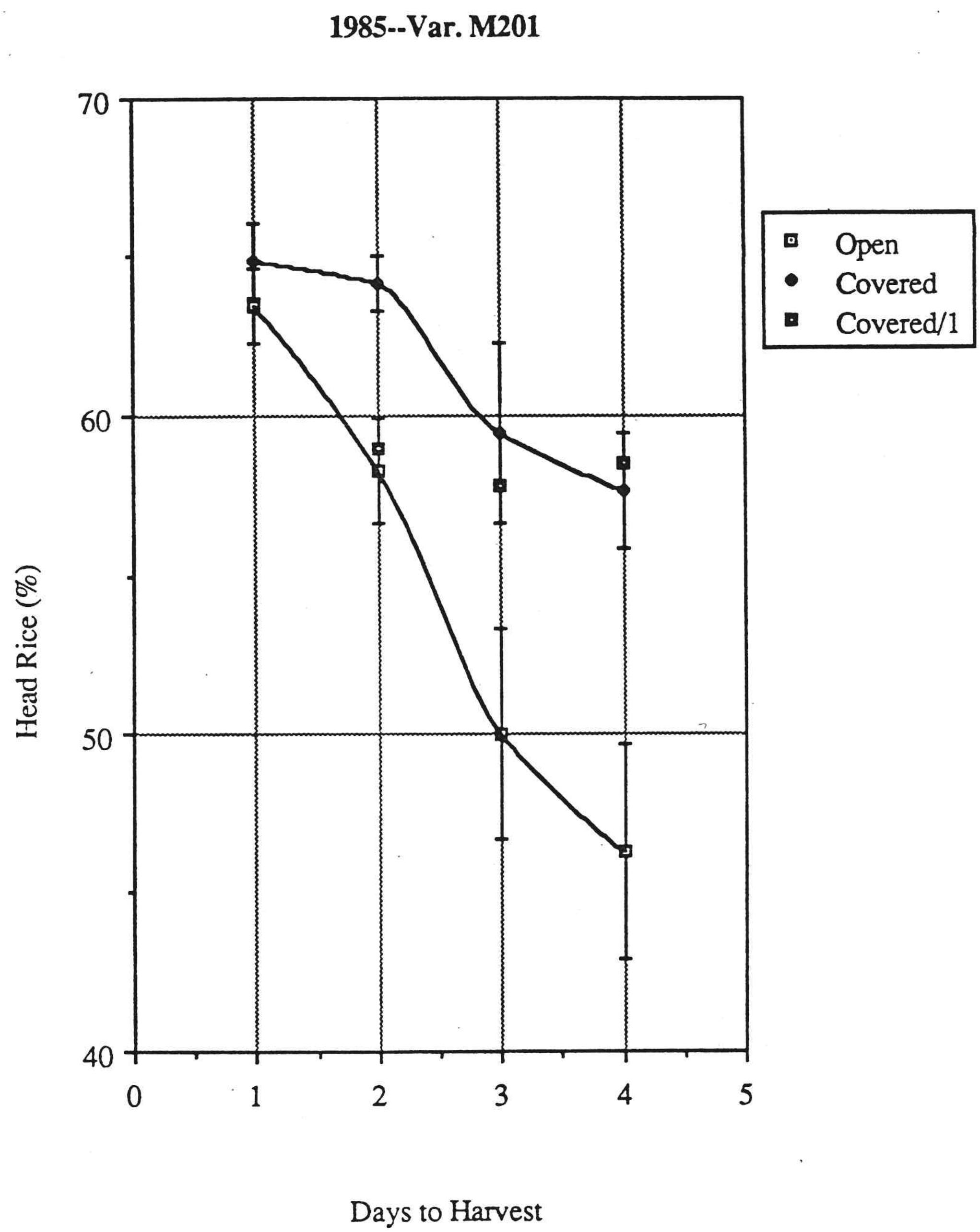


Figure 1. Head rice yields from the 1985 swath harvesting field trial in medium grain variety M201. The covered treatment was accomplished by folding the windrows. The terminology Covered/1 refers to windrows folded one day following swathing. Error bars are one standard deviation.

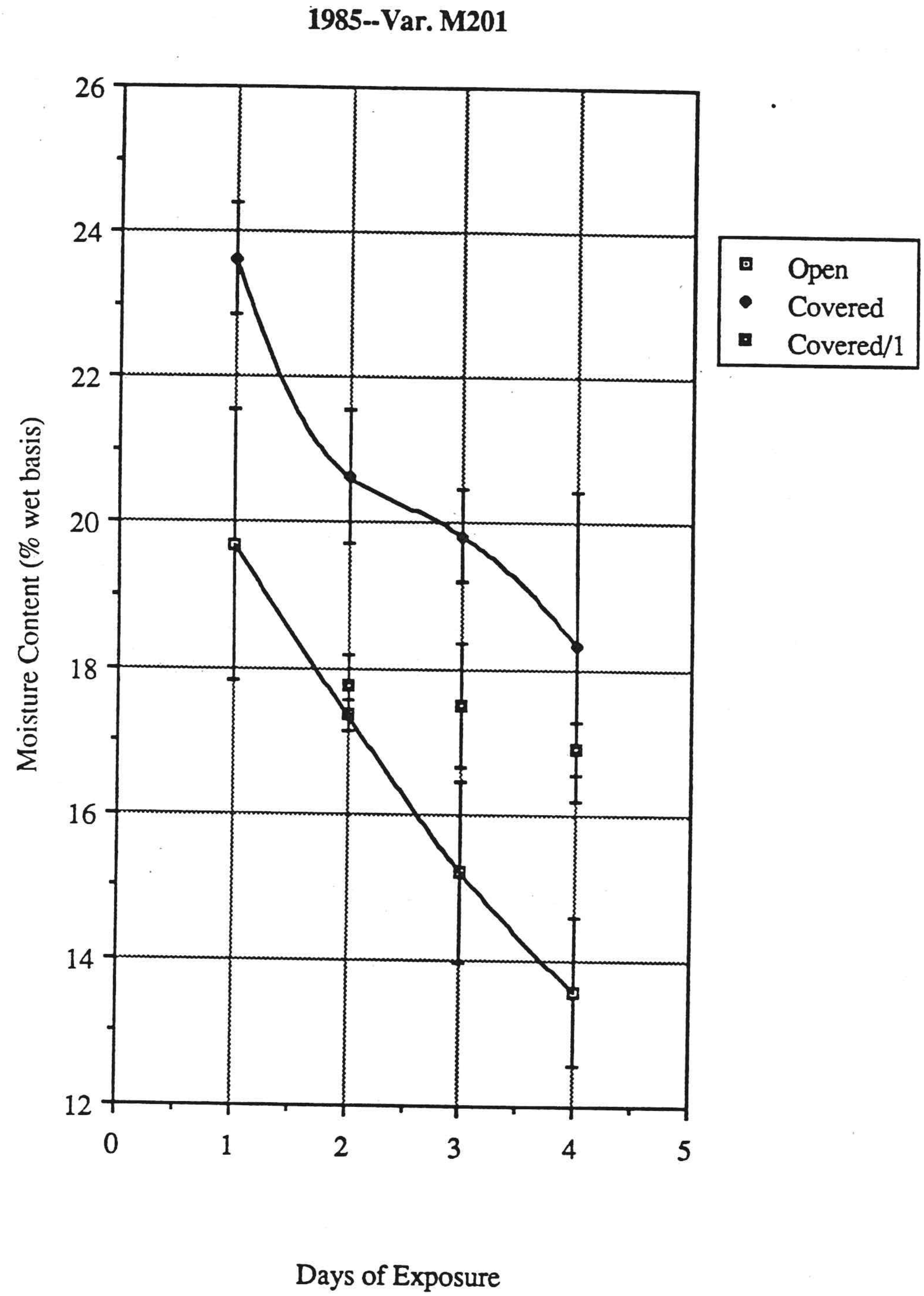


Figure 2. Grain moisture at harvest during the 1985 swath harvesting field trial.

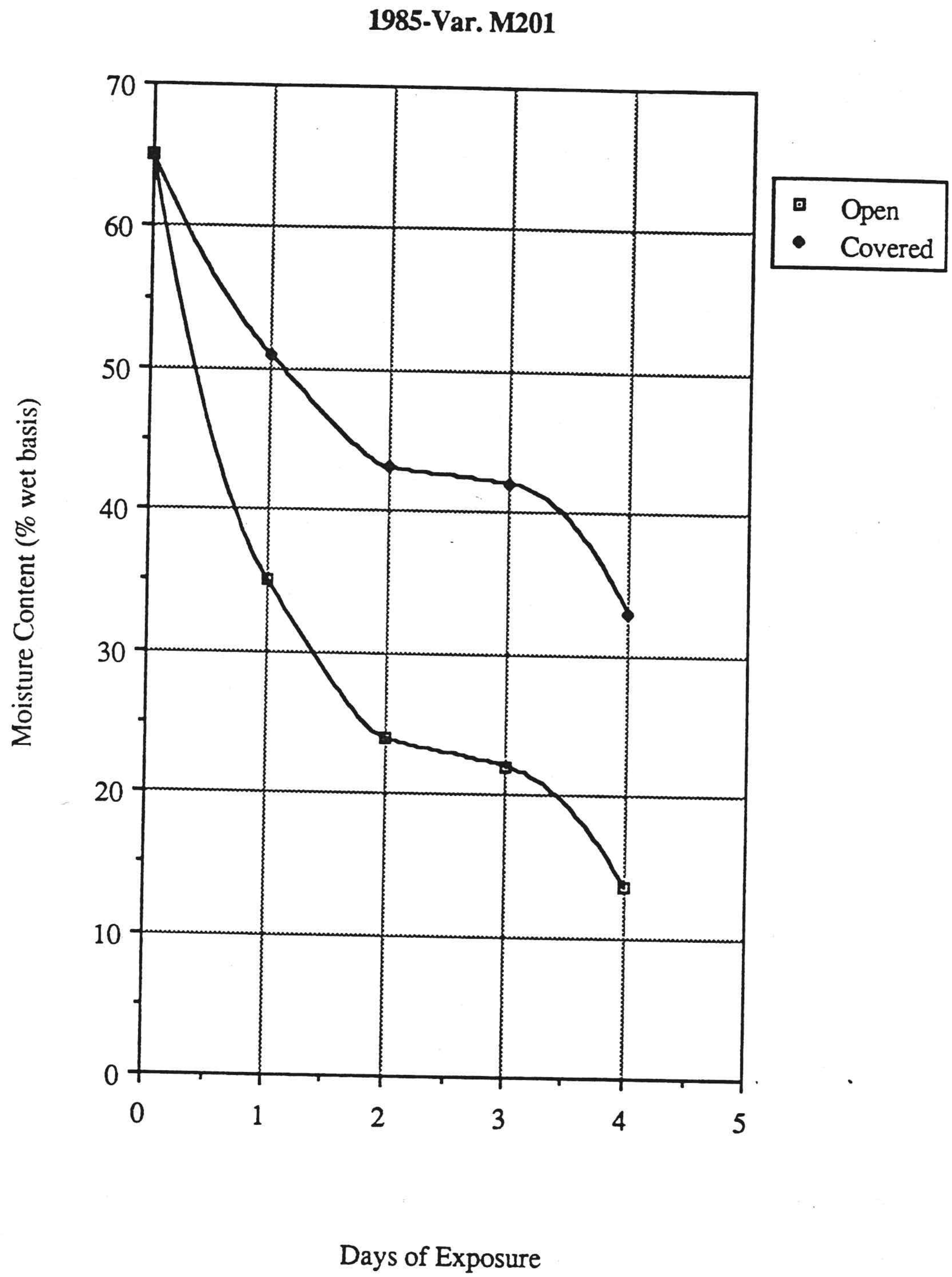


Figure 3. Straw moisture at harvest during the 1985 swath harvesting field trial.

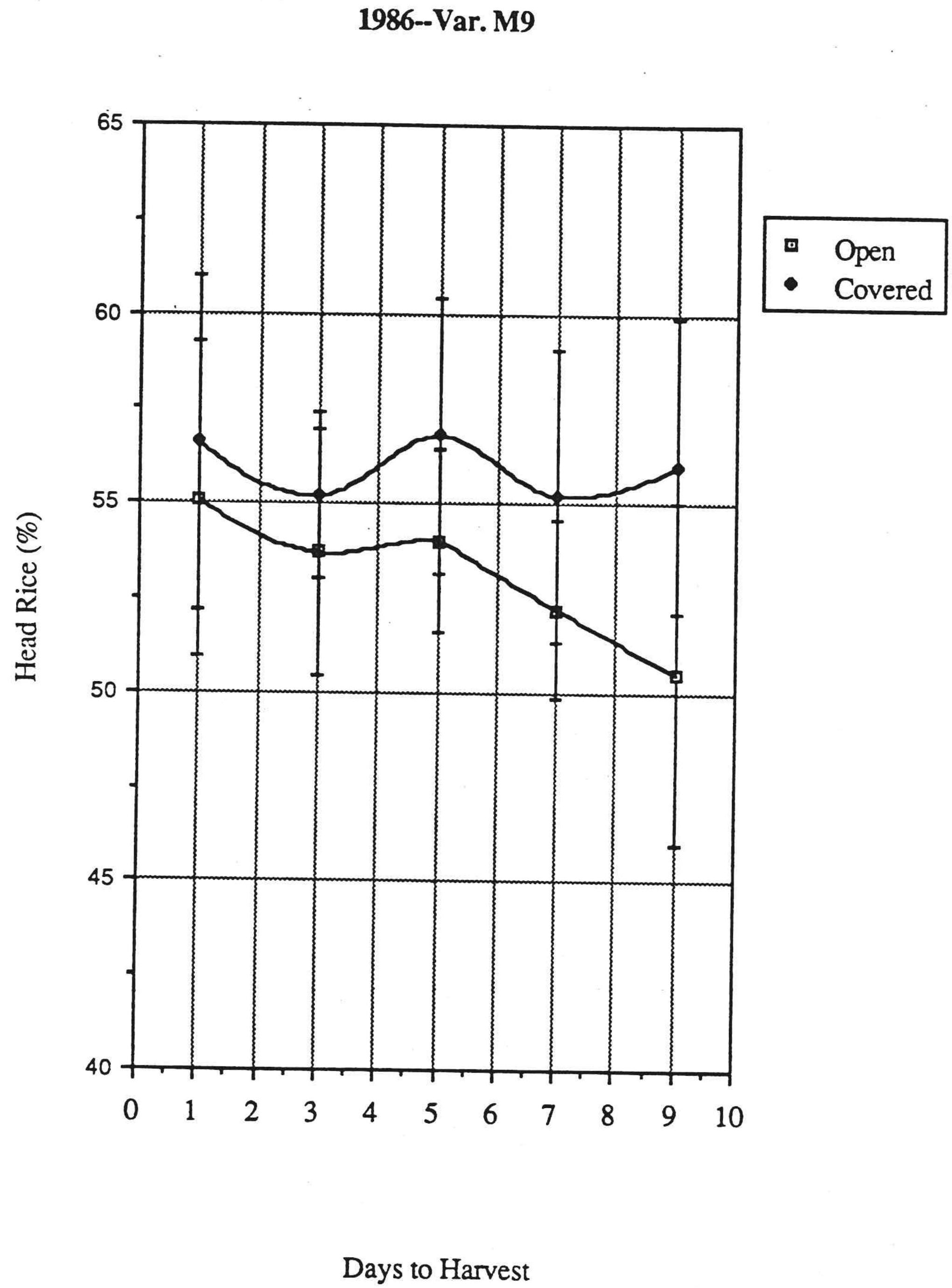


Figure 4. Head rice yields from the 1986 swath harvesting field trial in medium grain variety M9. The covered treatment was accomplished with chopped stubble cut from the side of the windrows.

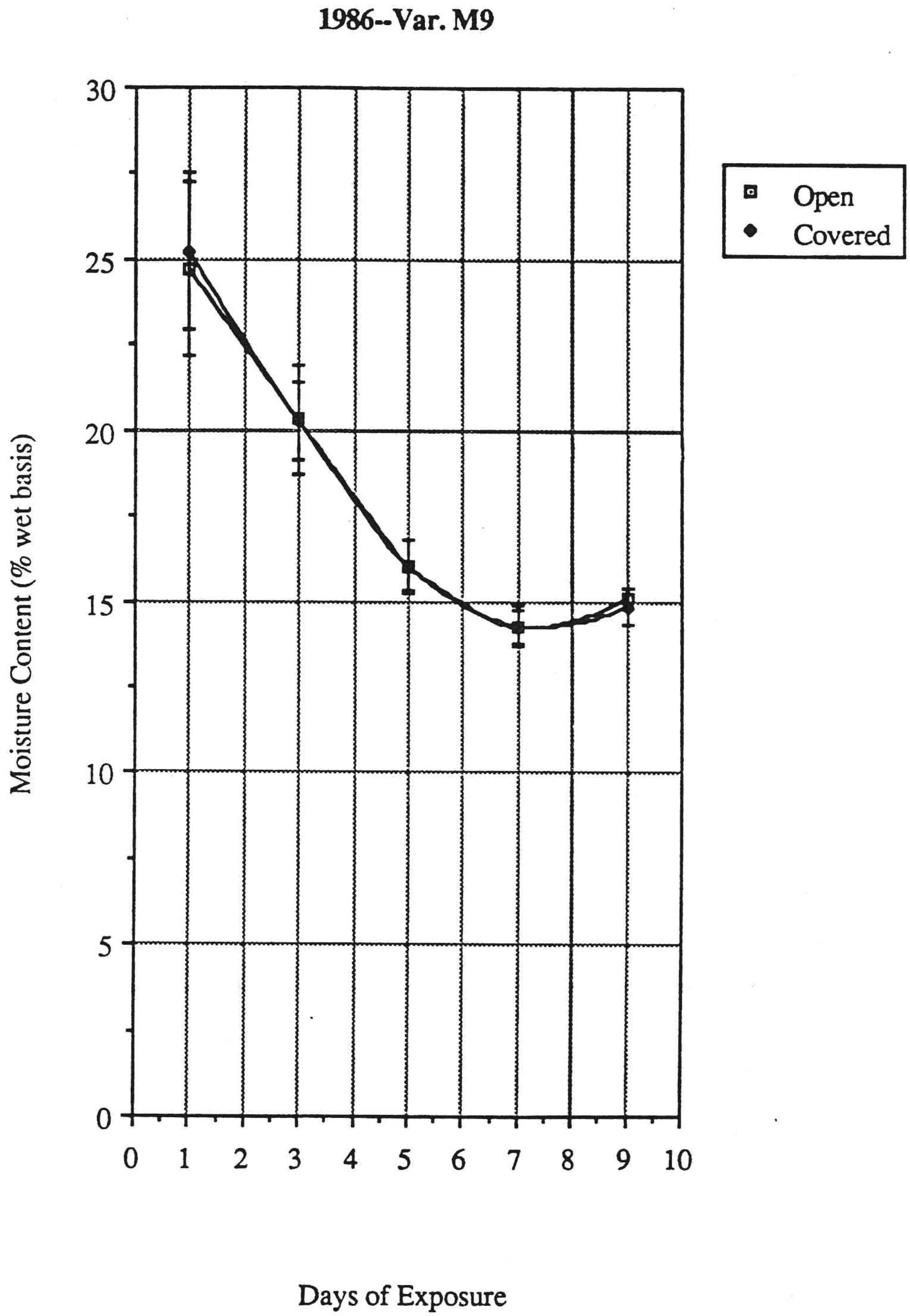


Figure 5. Grain moisture at harvest during the 1986 swath harvesting field trial.

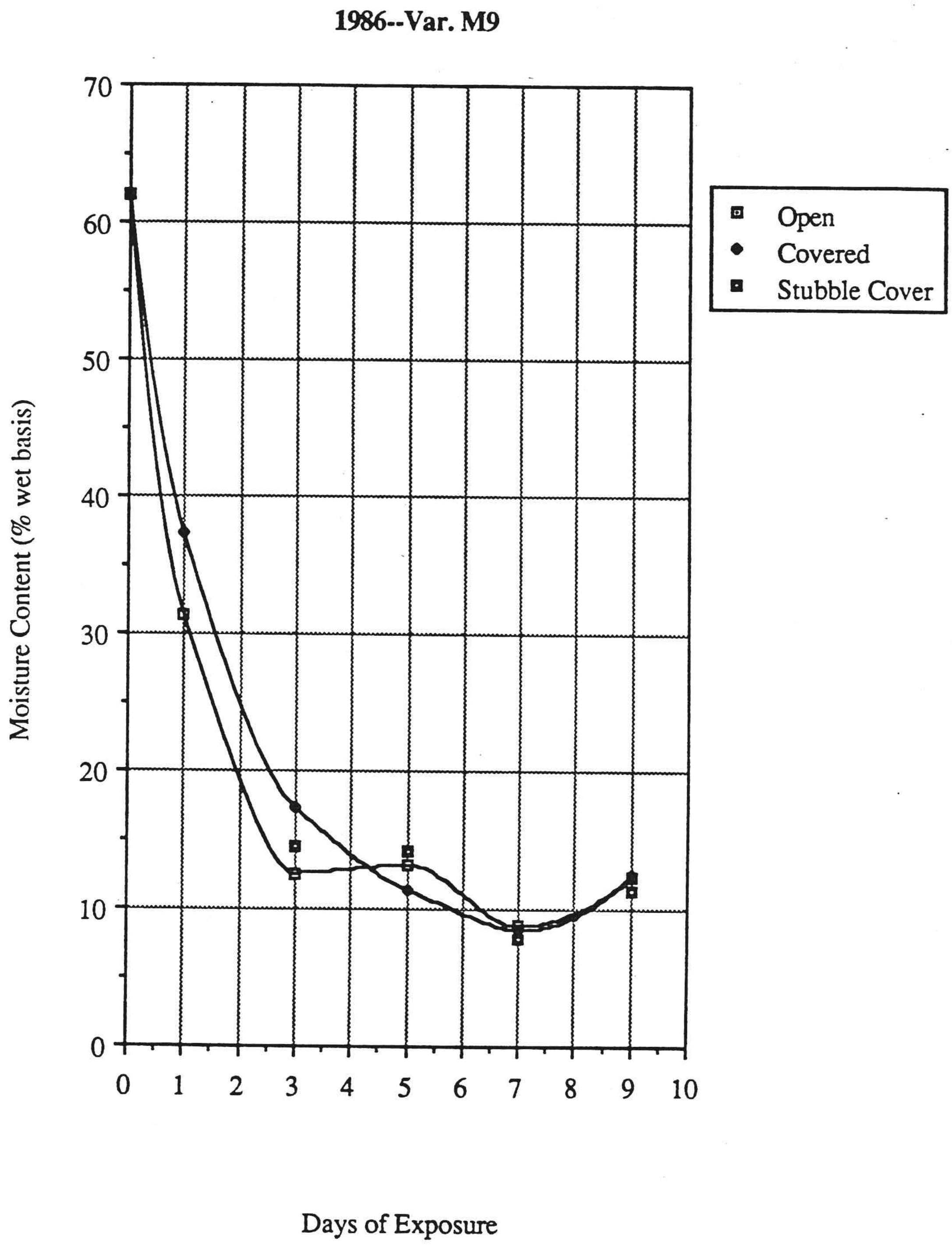


Figure 6. Straw and stubble cover moisture at harvest during the 1986 swath harvesting field trial.

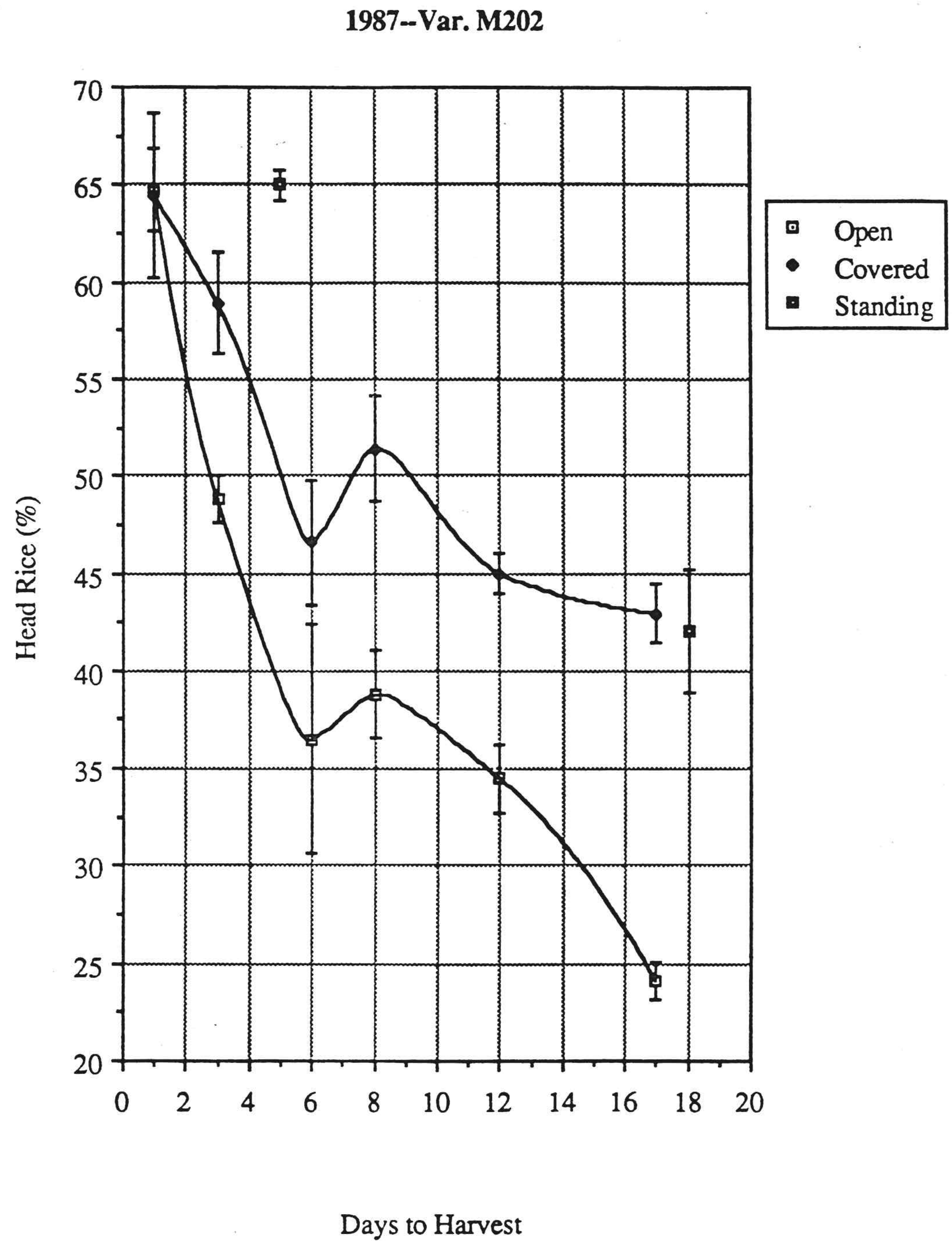


Figure 7. Head rice yields from the 1987 swath harvesting field trials in medium grain variety M202. The covered treatment was accomplished in the same manner used in 1986.

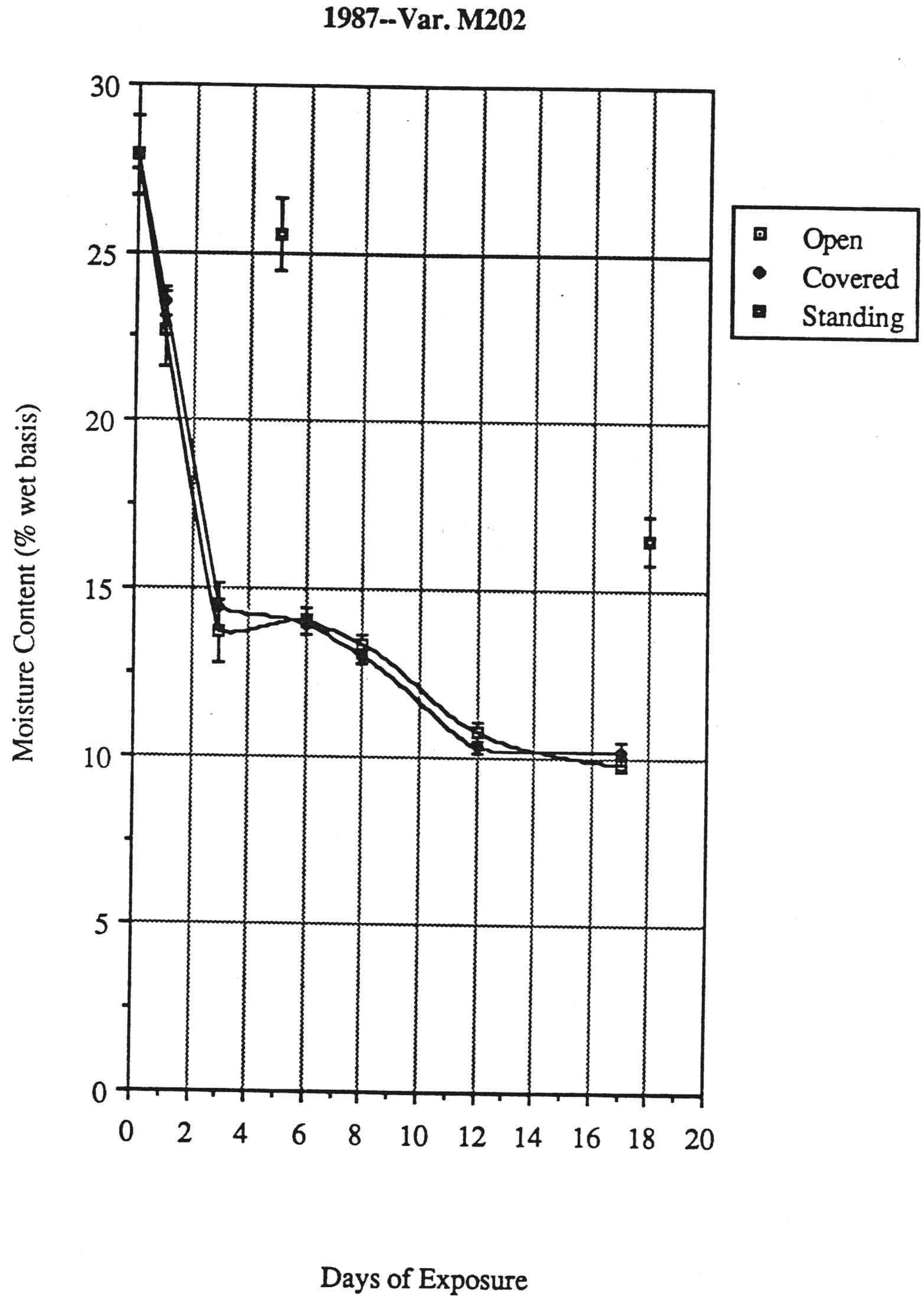


Figure 8. Grain moisture at harvest throughout the 1987 field trial.

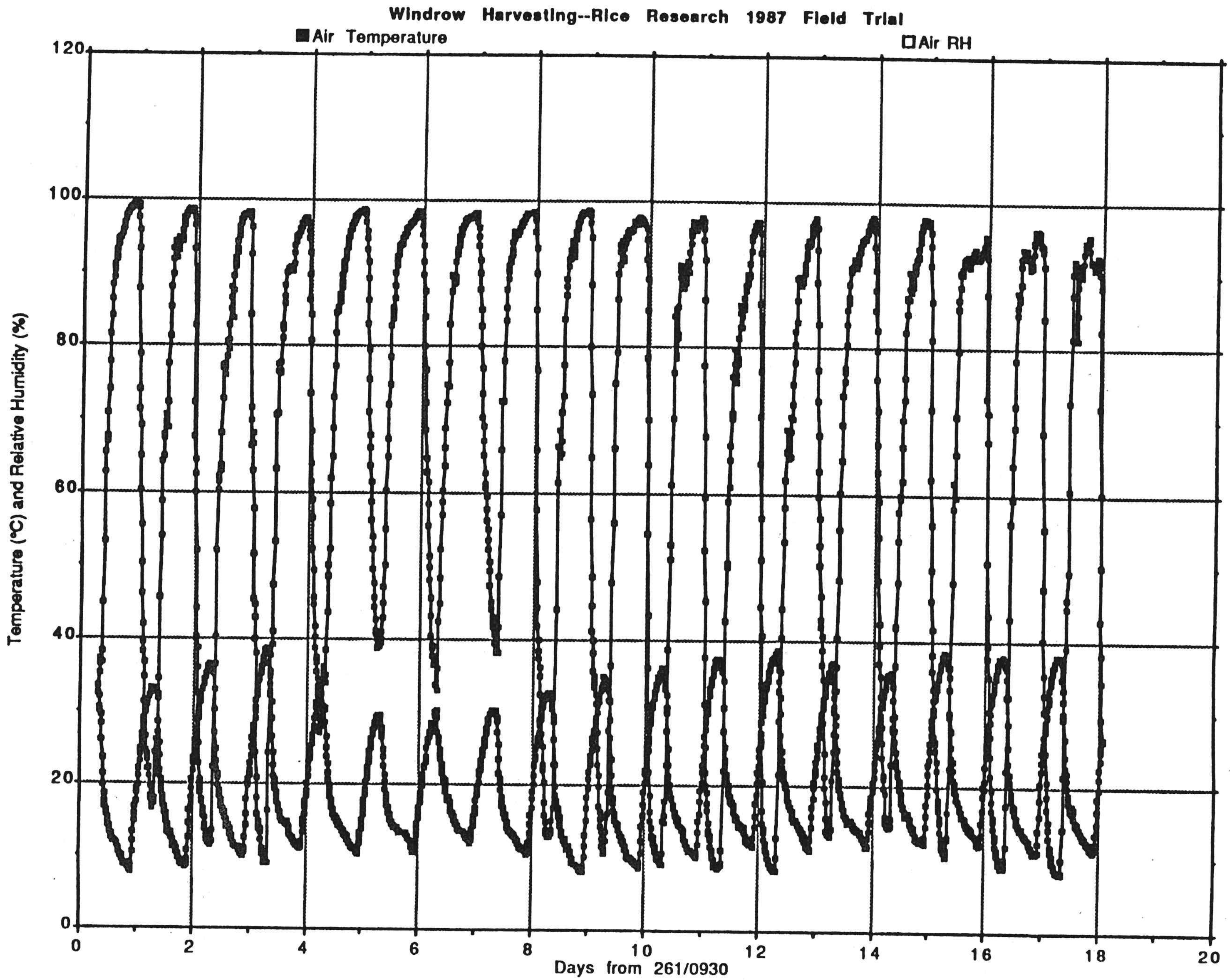


Figure 9. Air temperature and relative humidity at the windrow surface throughout the 1987 field trial.

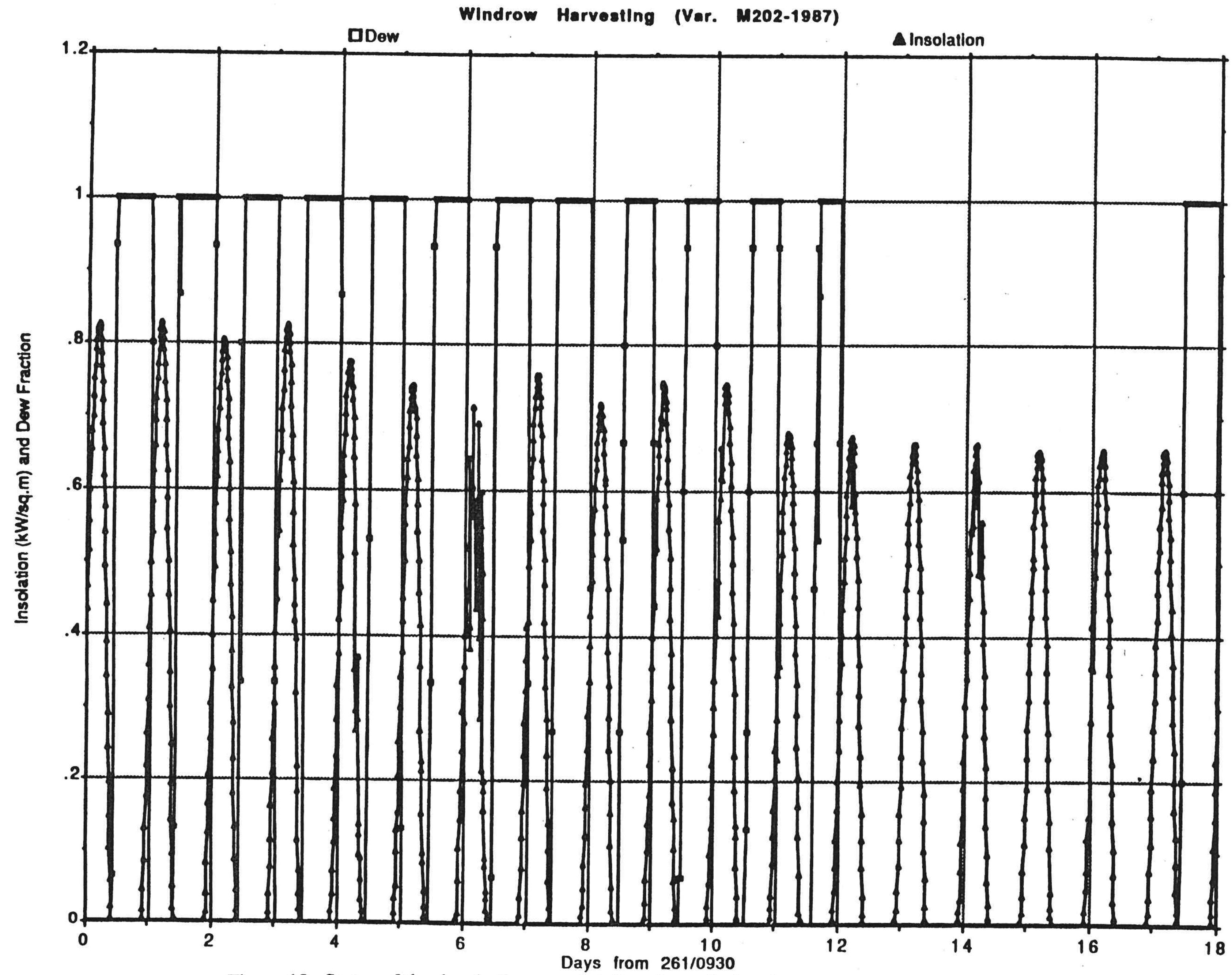


Figure 10. Status of the dew indicator and daily solar radiation throughout the 1987 field trial. The dew sensor was located on the surface of the windrow through day 12 and from day 17 to 18. The sensor was located beneath the stubble cover days 13 to 17.

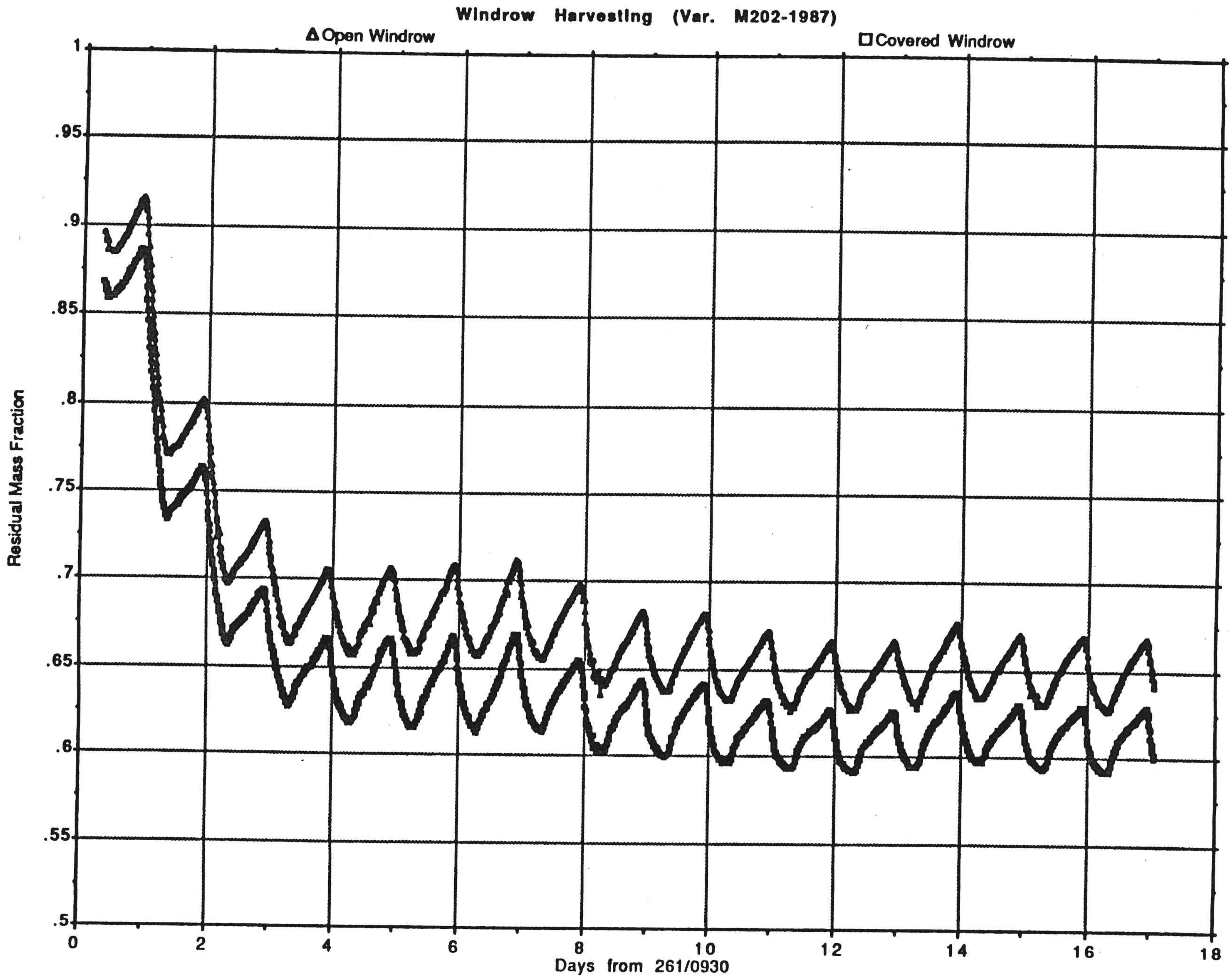


Figure 11. Load cell response for 2.2 m^2 sections of open and covered windrows throughout the 1987 field trial.

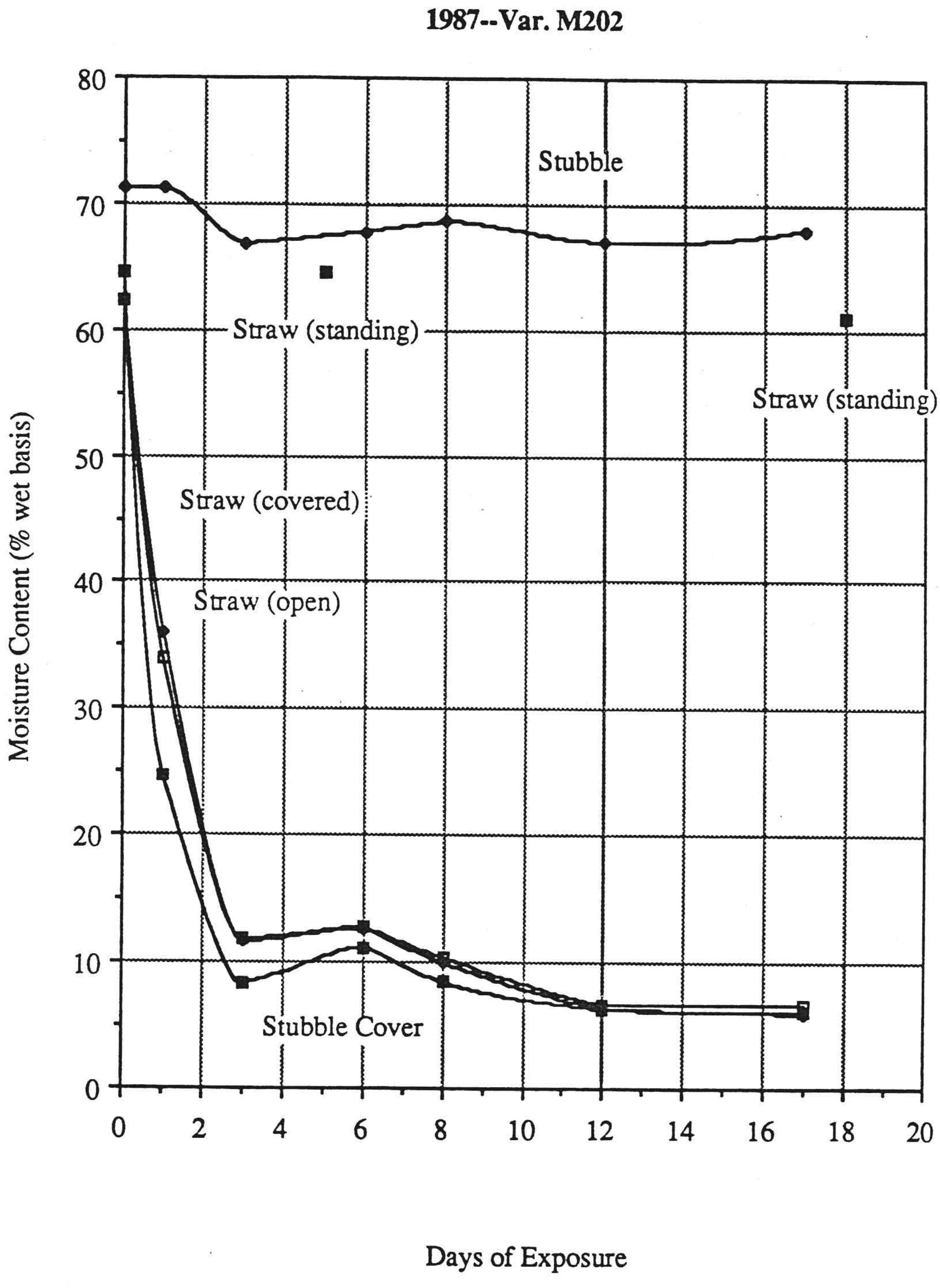


Figure 12. Moisture content of straw in the windrows, stubble cover, and uncut straw and stubble during the 1987 field trial.

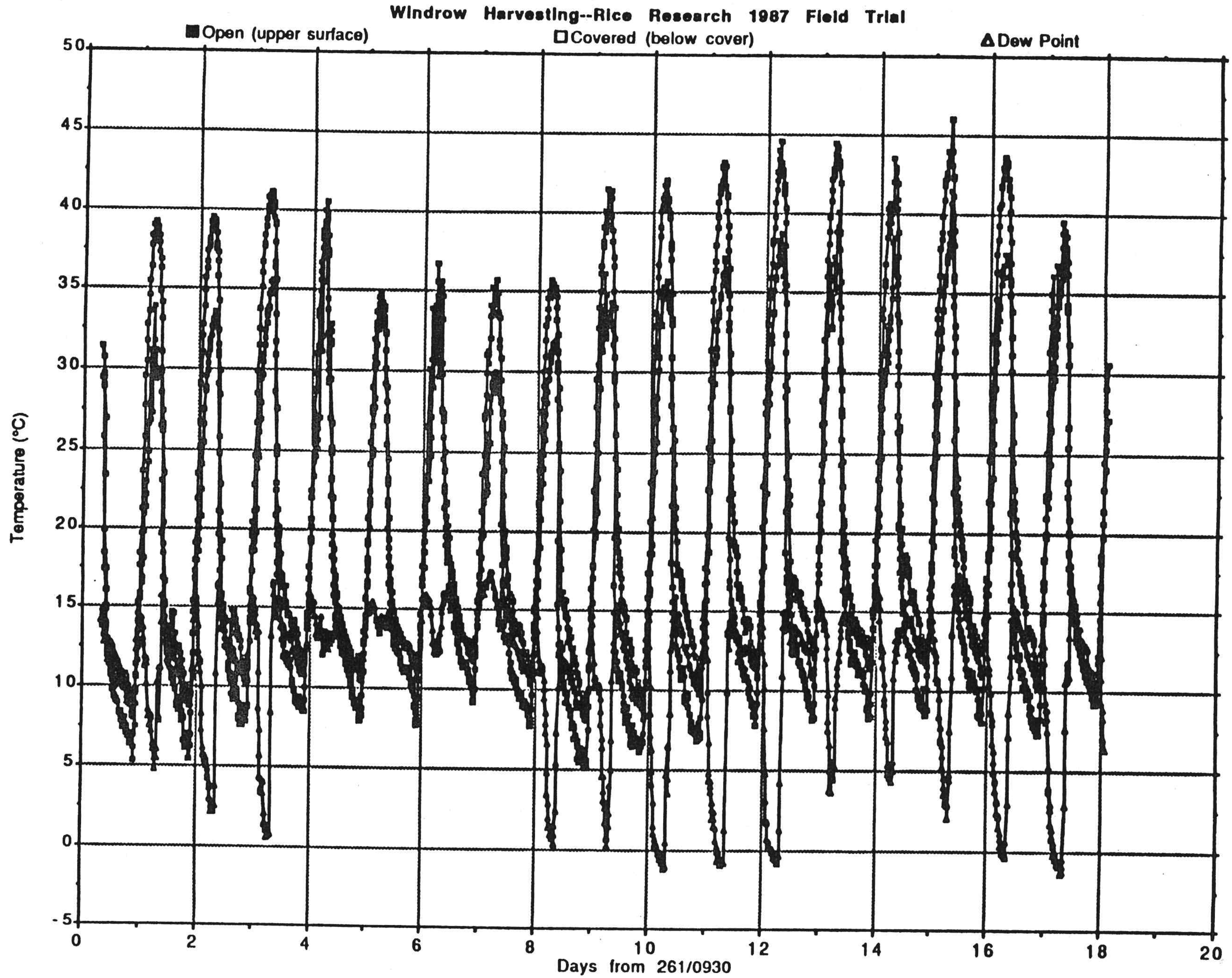


Figure 13. Temperatures at the windrow surface and beneath the stubble cover compared to dew point temperature throughout the 1987 field trial.

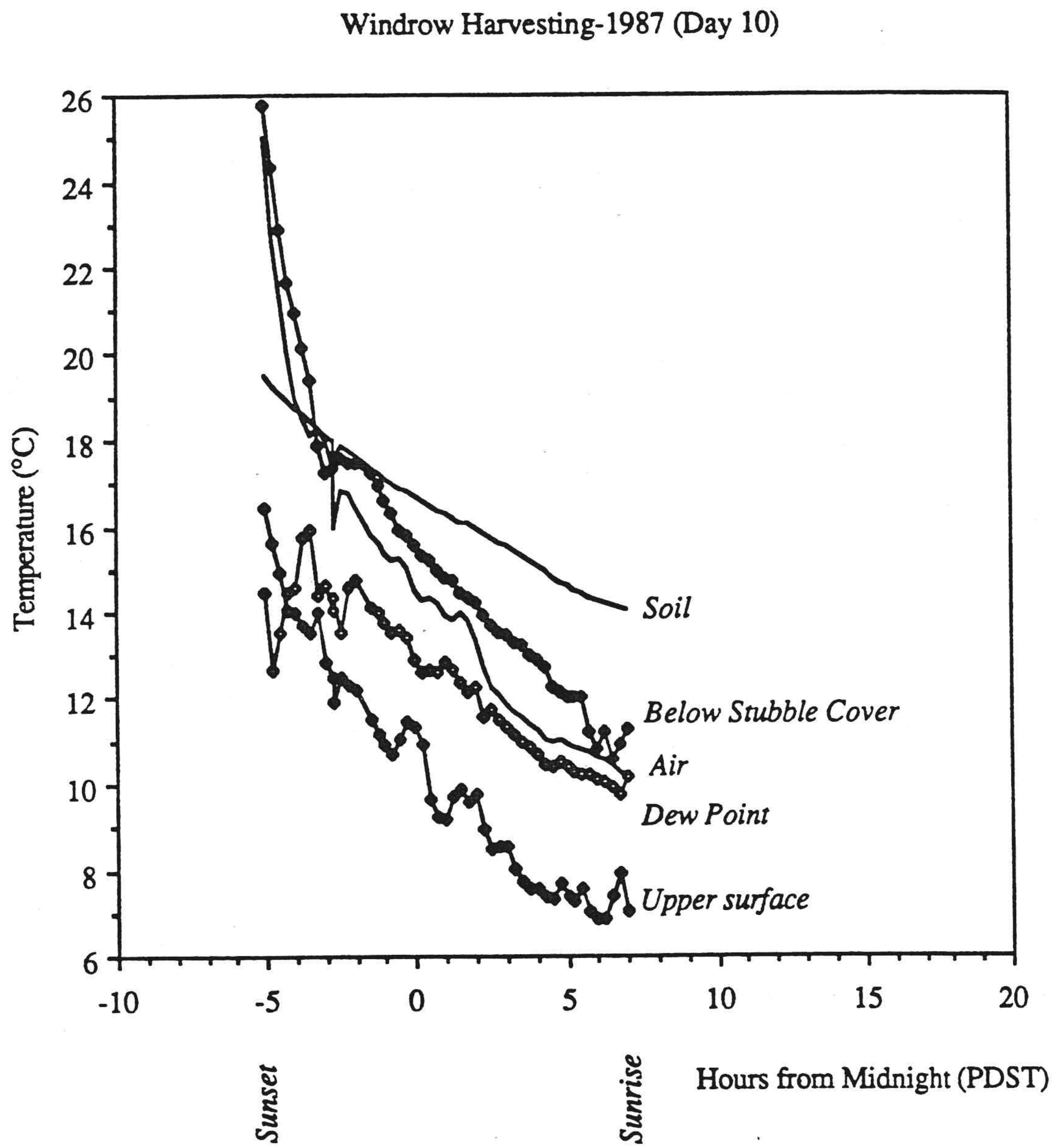
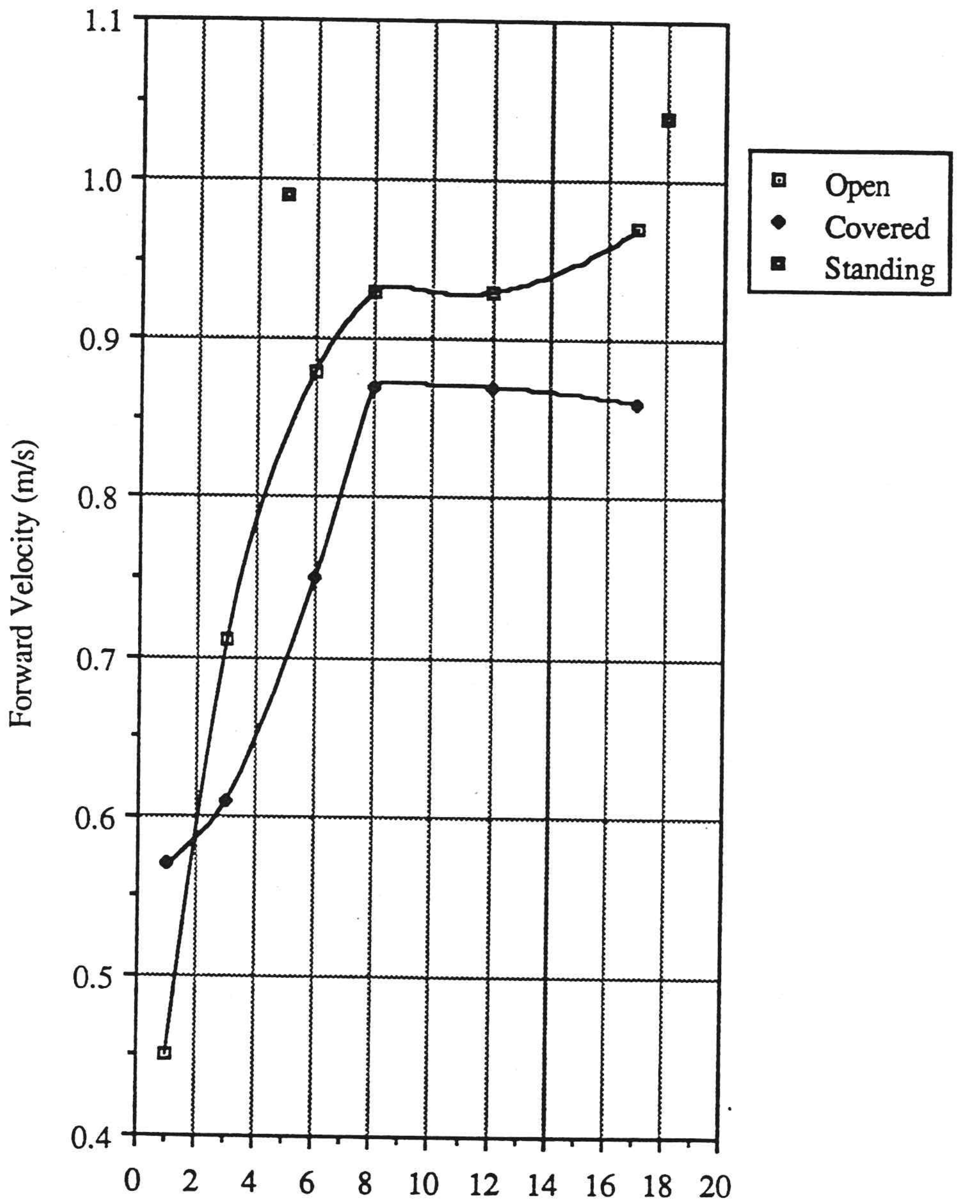


Figure 14. Temperature data for the night of day 10 during the 1987 field trial.

1987--Var. M202



Days to Harvest

Figure 15. Harvester speed measured during the 1987 field trial.

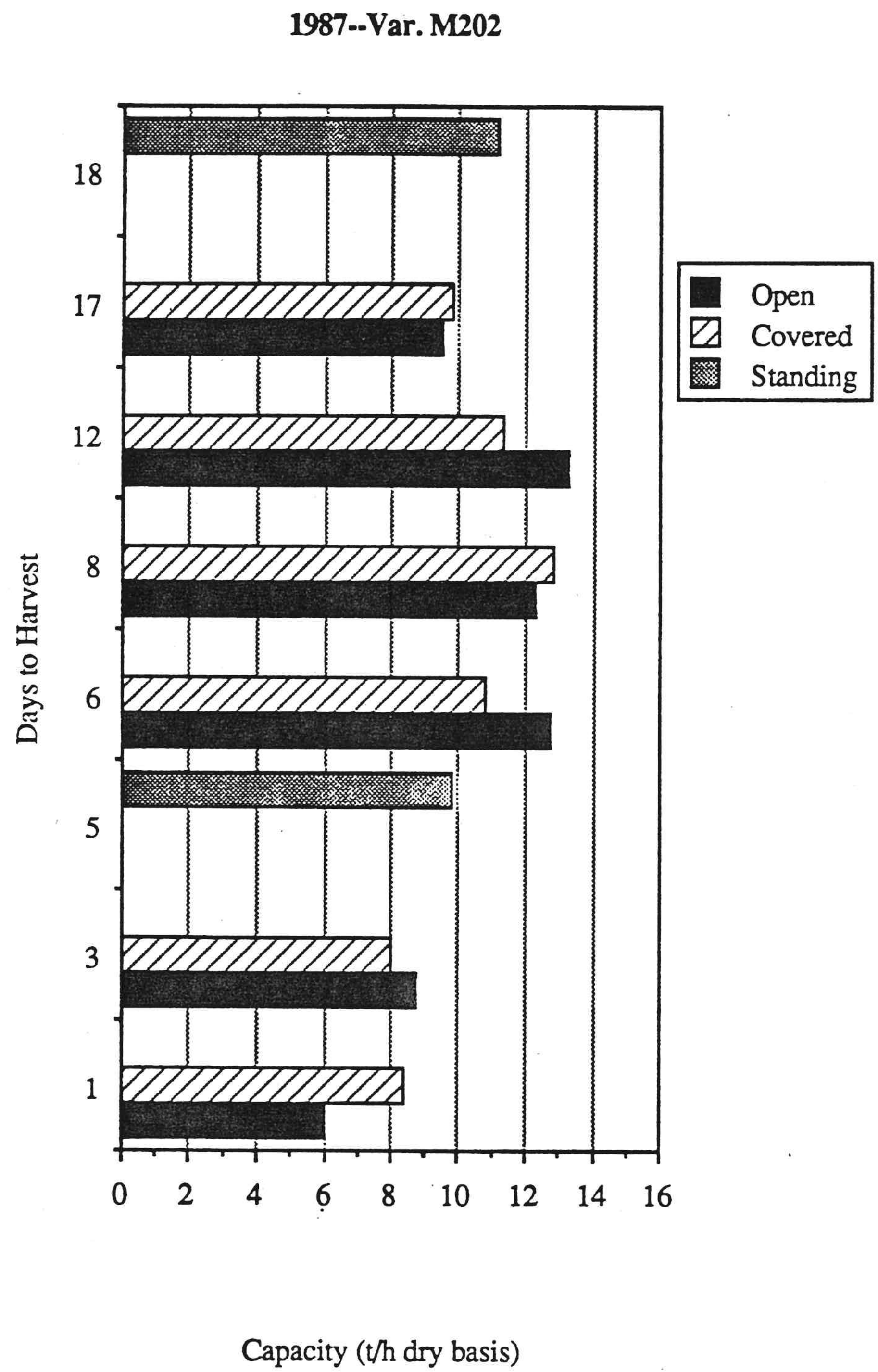


Figure 16. Harvester capacity based on forward velocity and harvested grain yield for the 1987 field trial.

1987--Var. M202

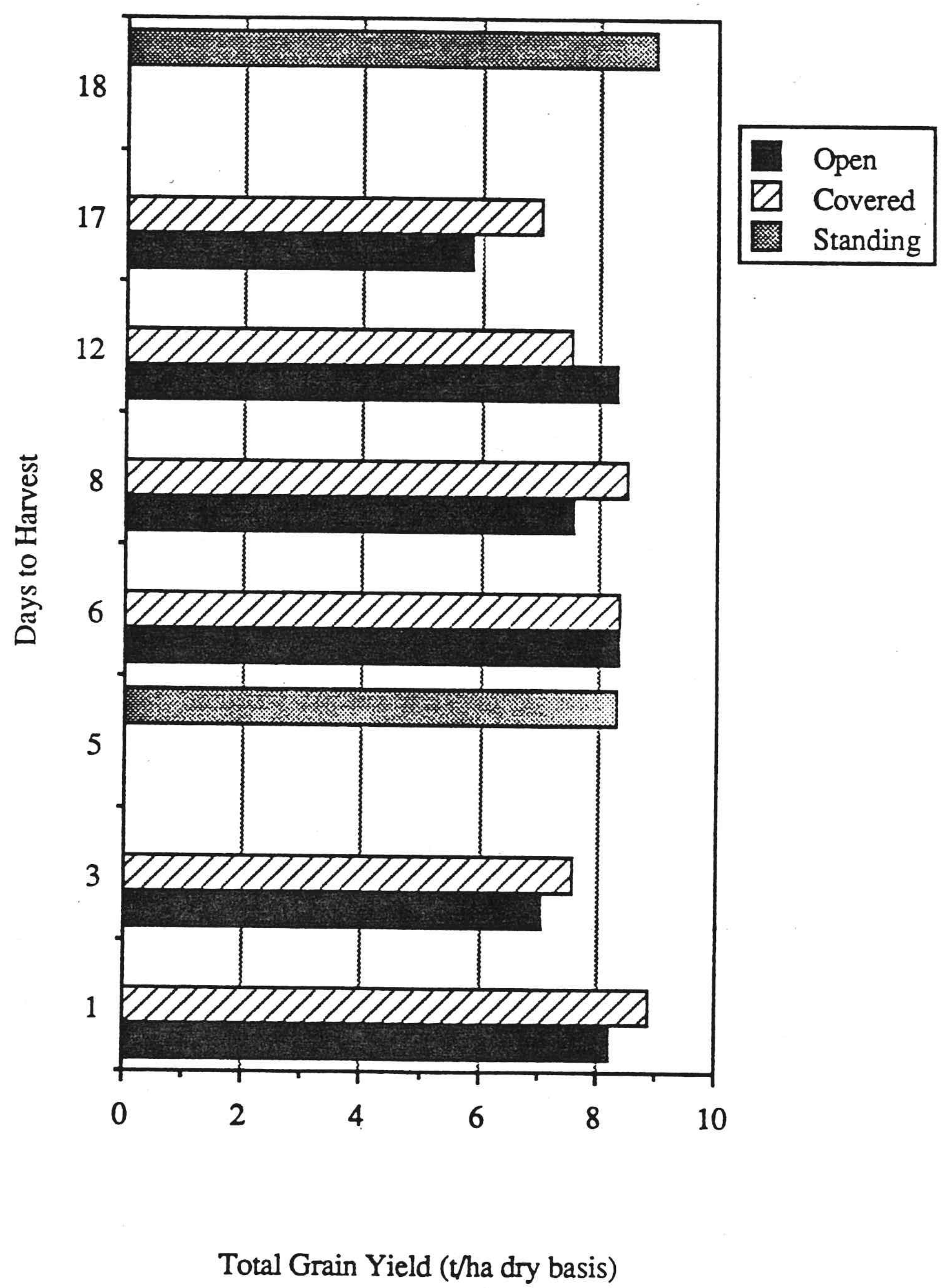


Figure 17. Total grain yields from each windrow and section during the 1987 field trial.

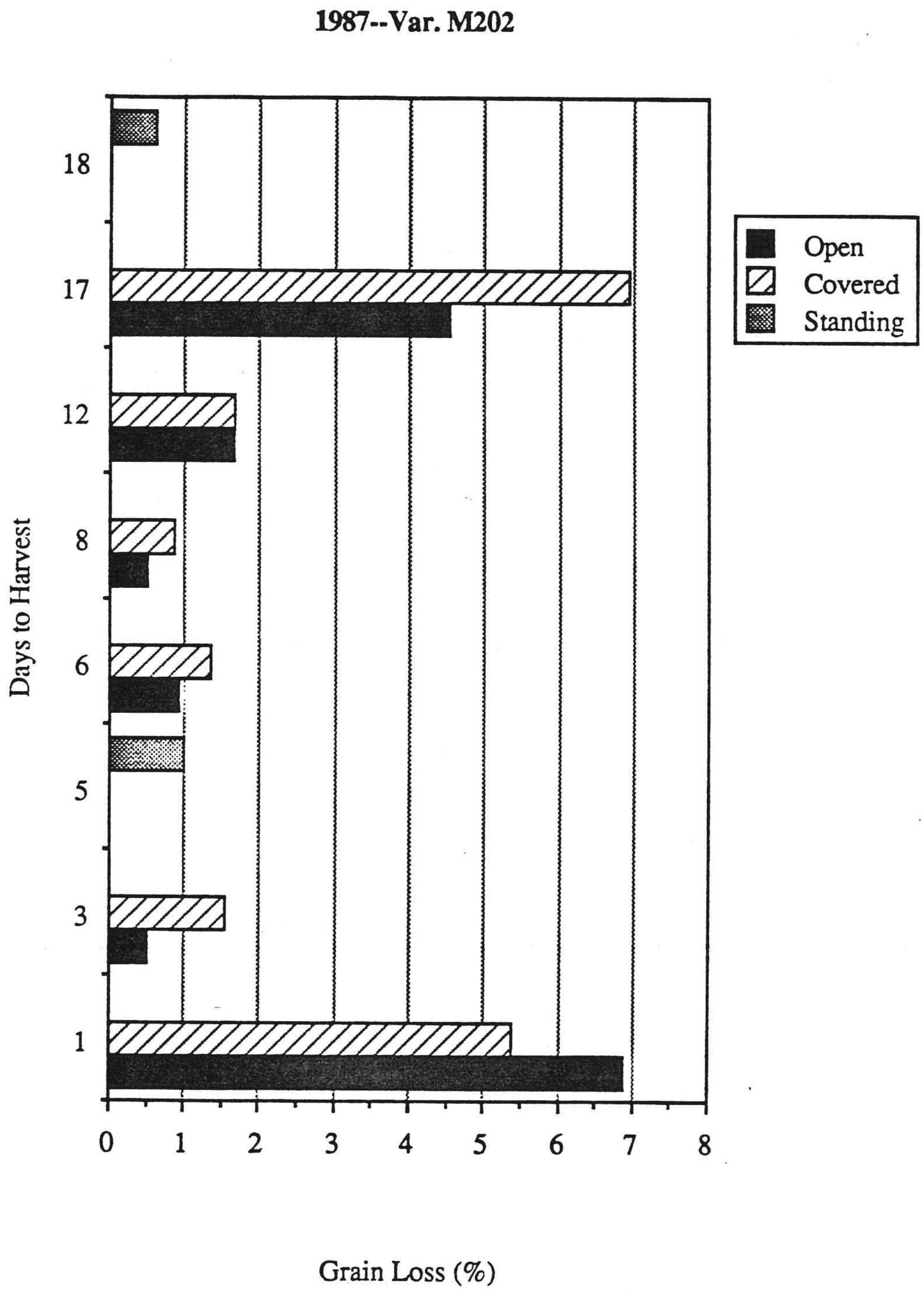


Figure 18. Grain losses measured by rethreshing the windrows, 1987 field trial.

1987--Var. M202

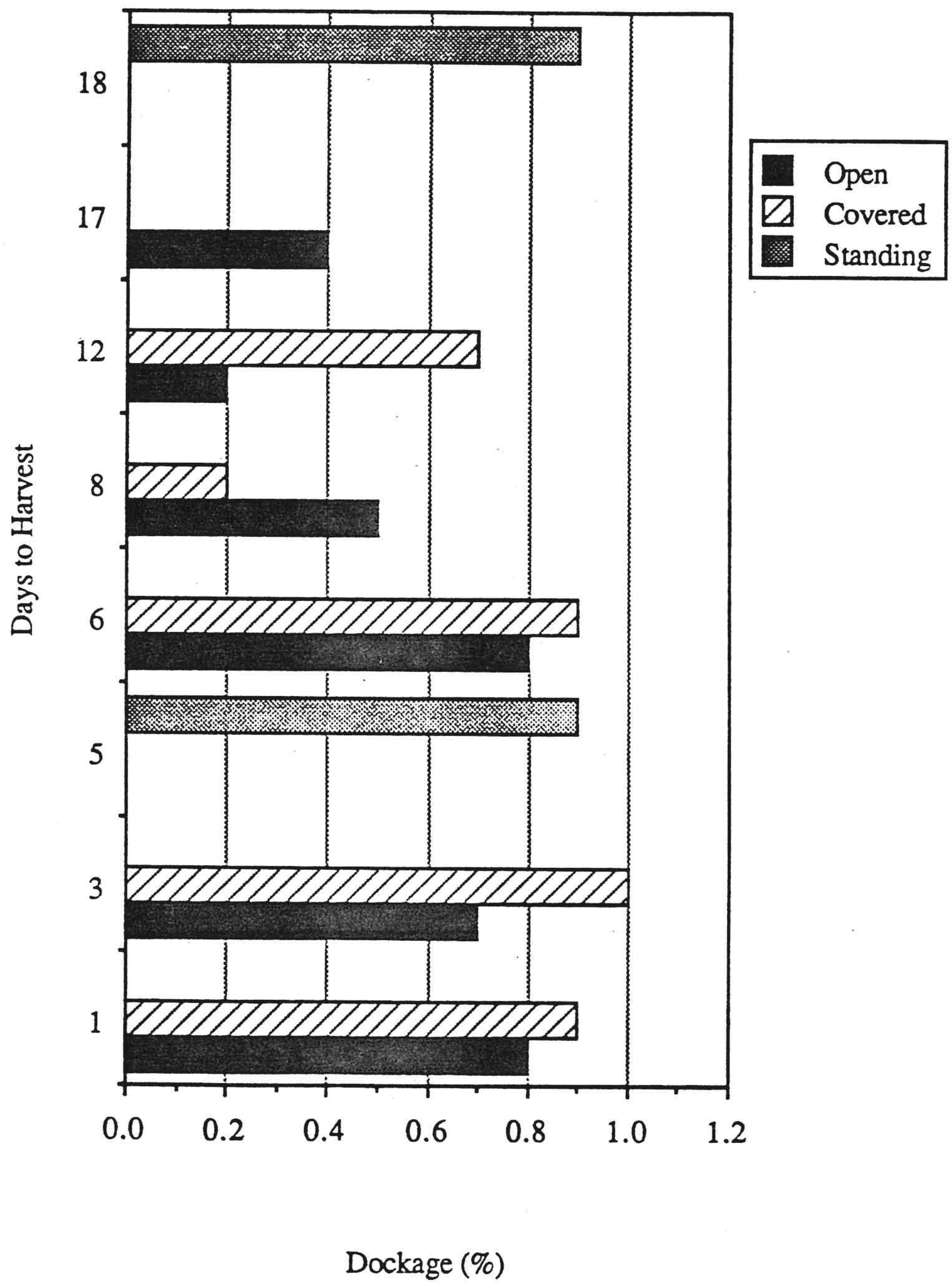


Figure 19. Dockage measured at milling, 1987 field trial.

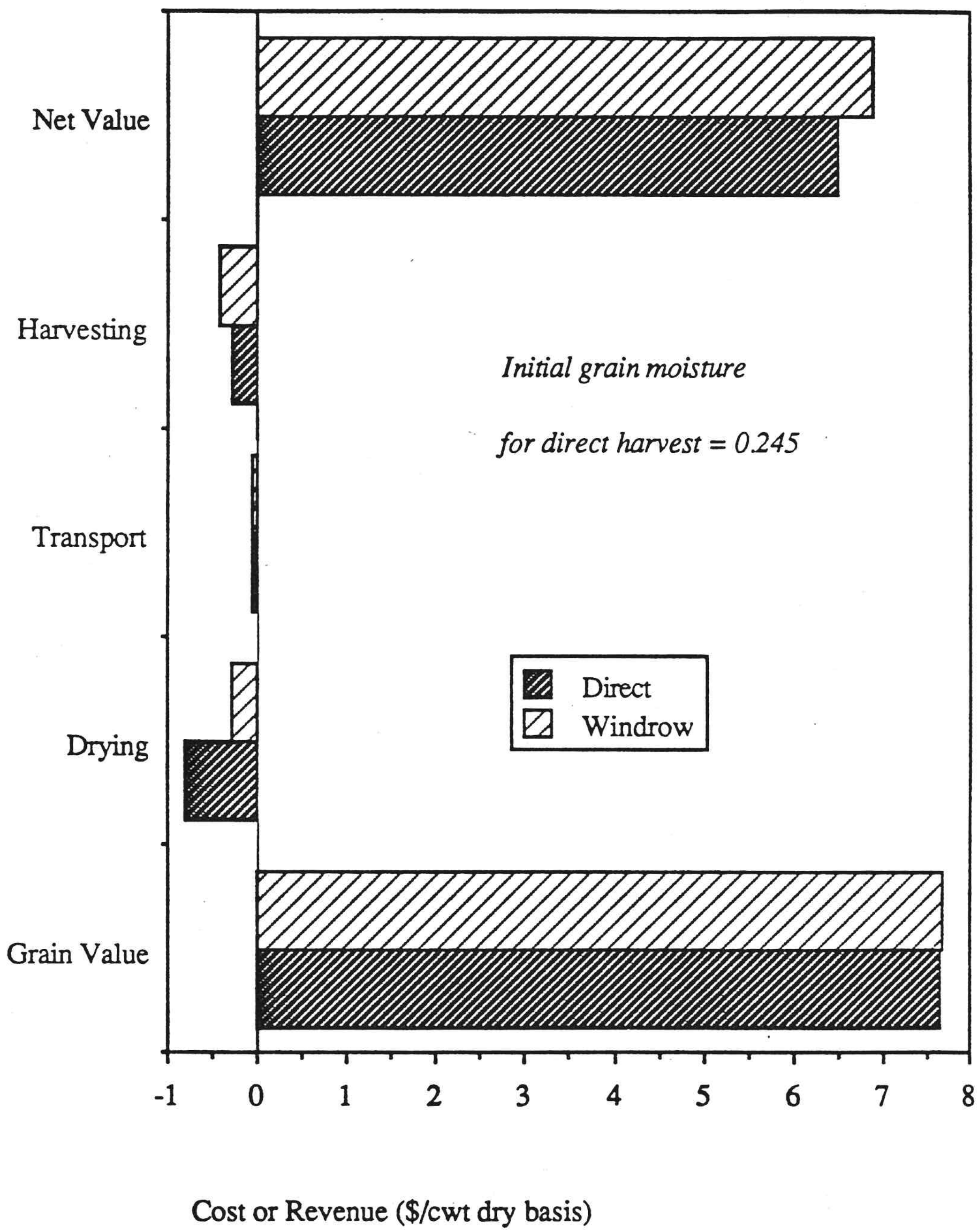


Figure 20. Comparison of direct and swath harvesting costs by category.

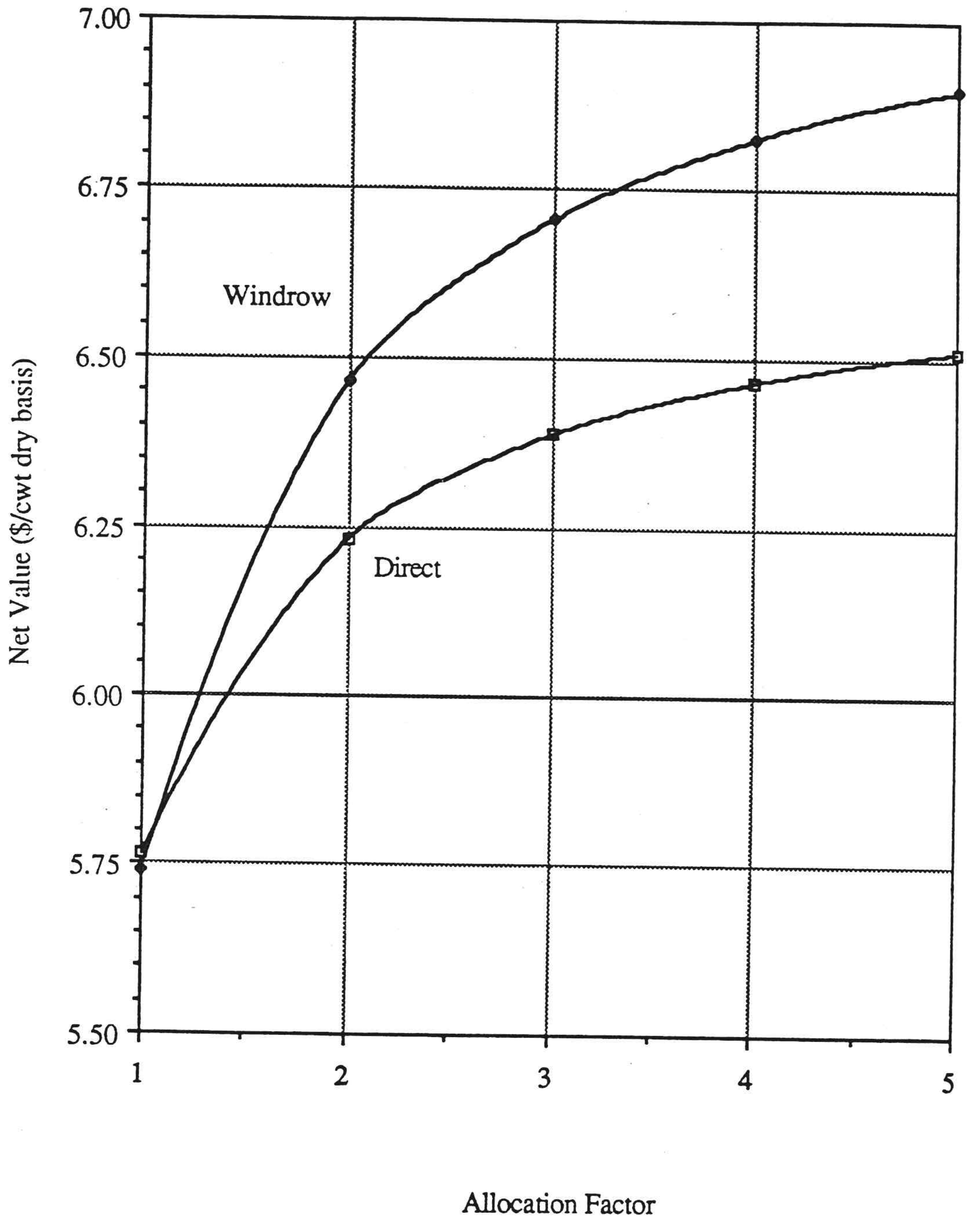


Figure 21. The effect of scale on net grain value for direct and swath harvesting.

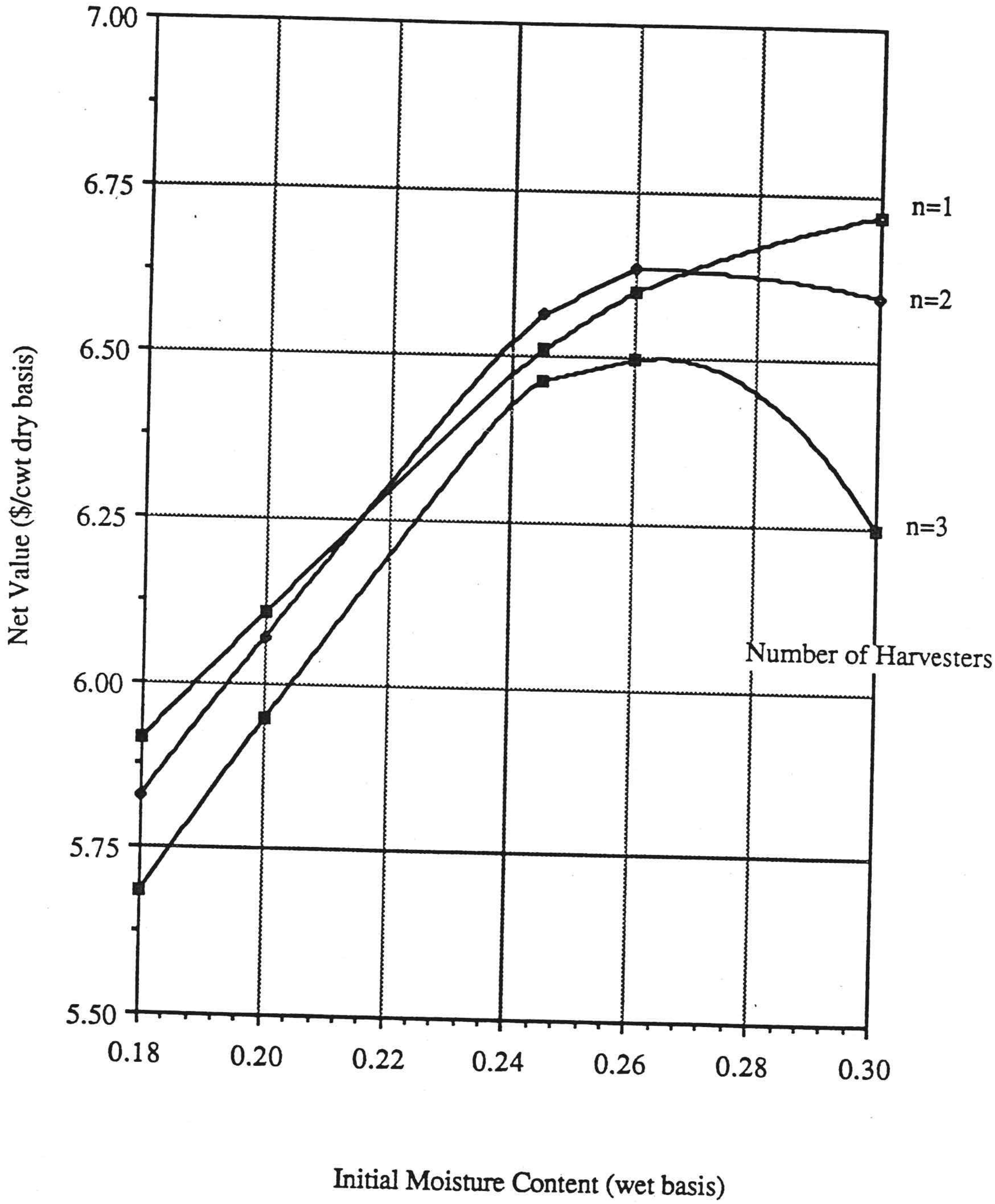


Figure 22. The influence of the starting grain moisture on the net grain value from direct harvesting.

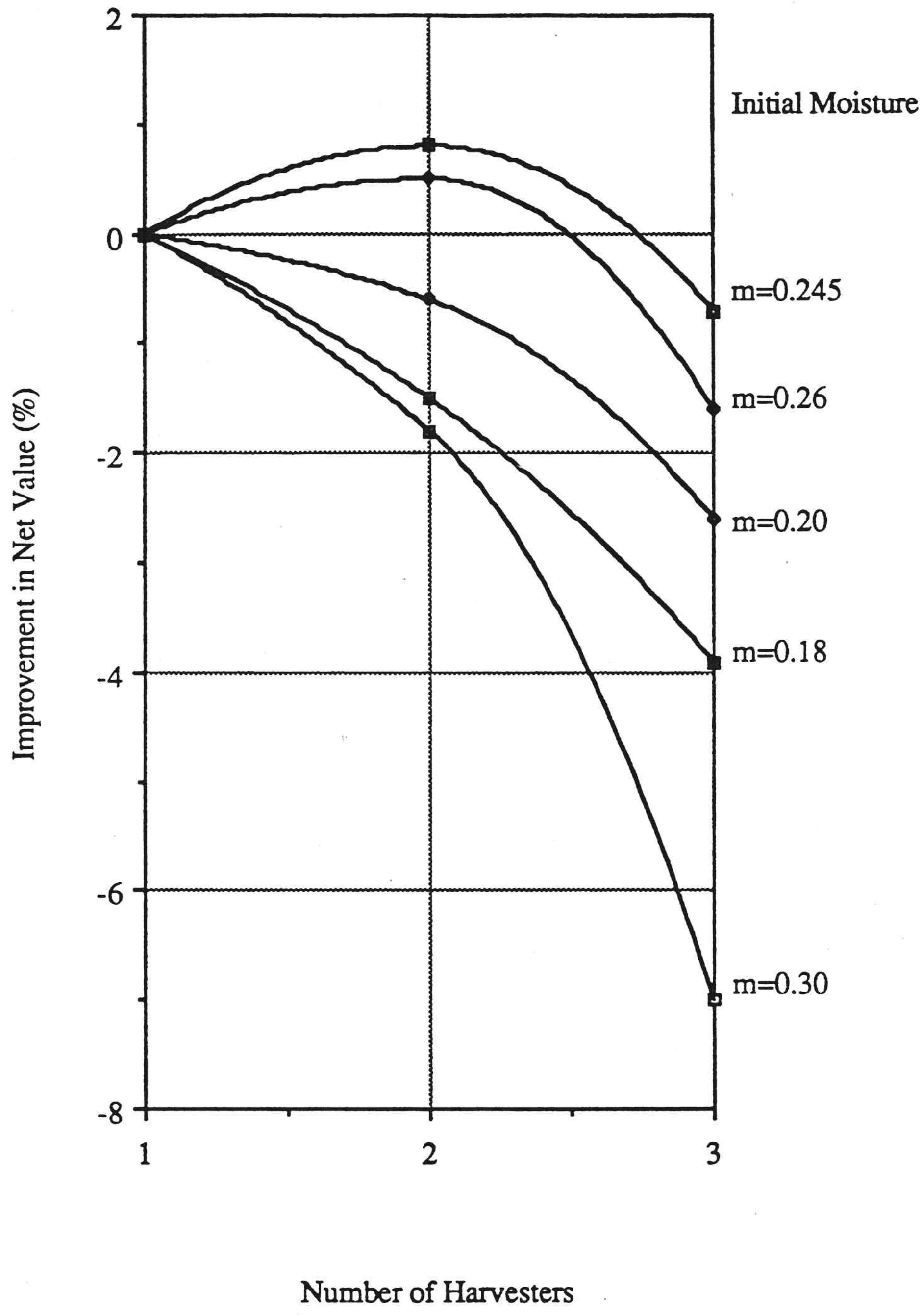


Figure 23. The influence of the number of harvesters on the relative improvement in the net grain value for direct harvesting.

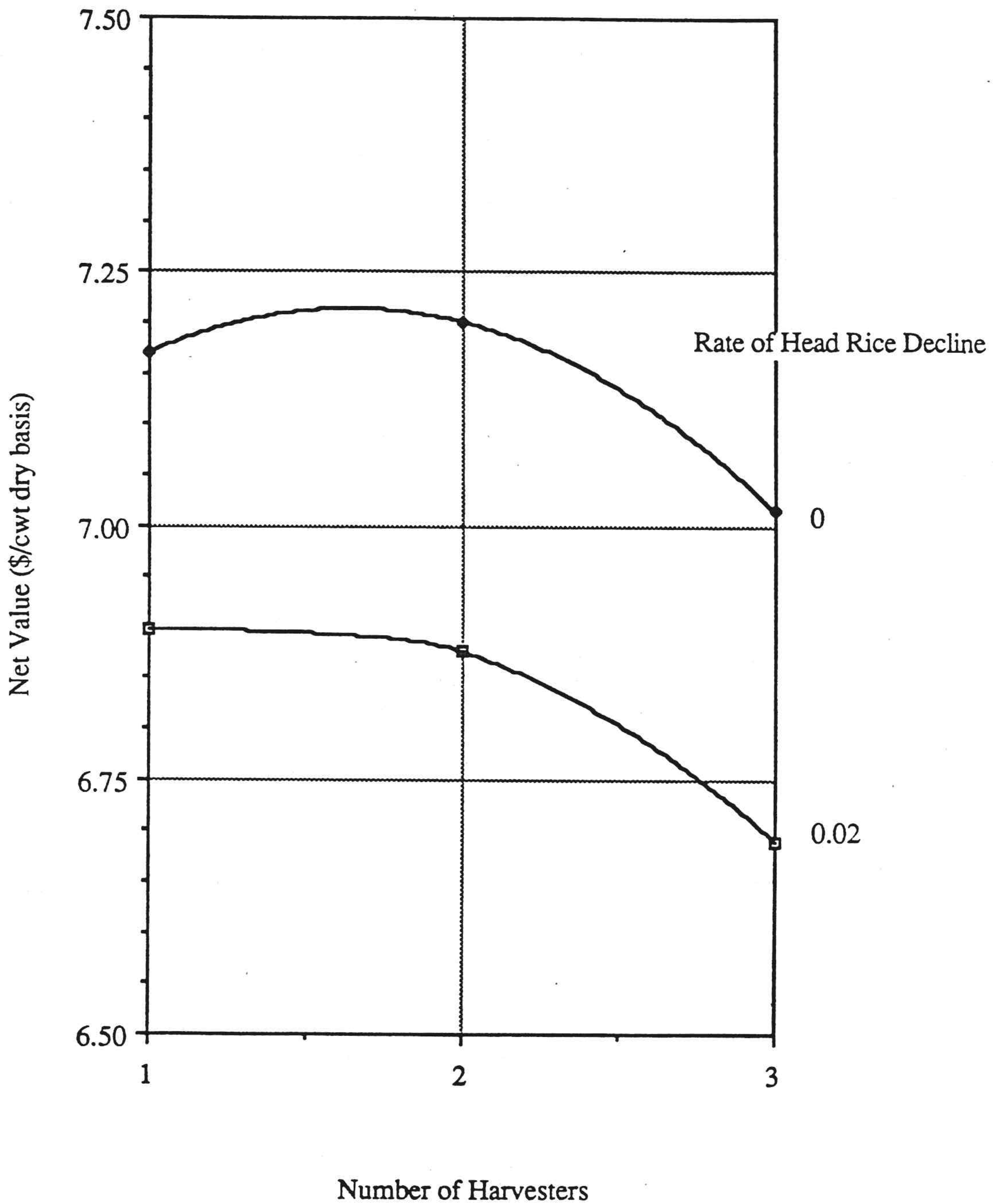


Figure 24. The effect of rate of head rice decline in the windrow and number of harvesters on the net grain value for swath harvesting.

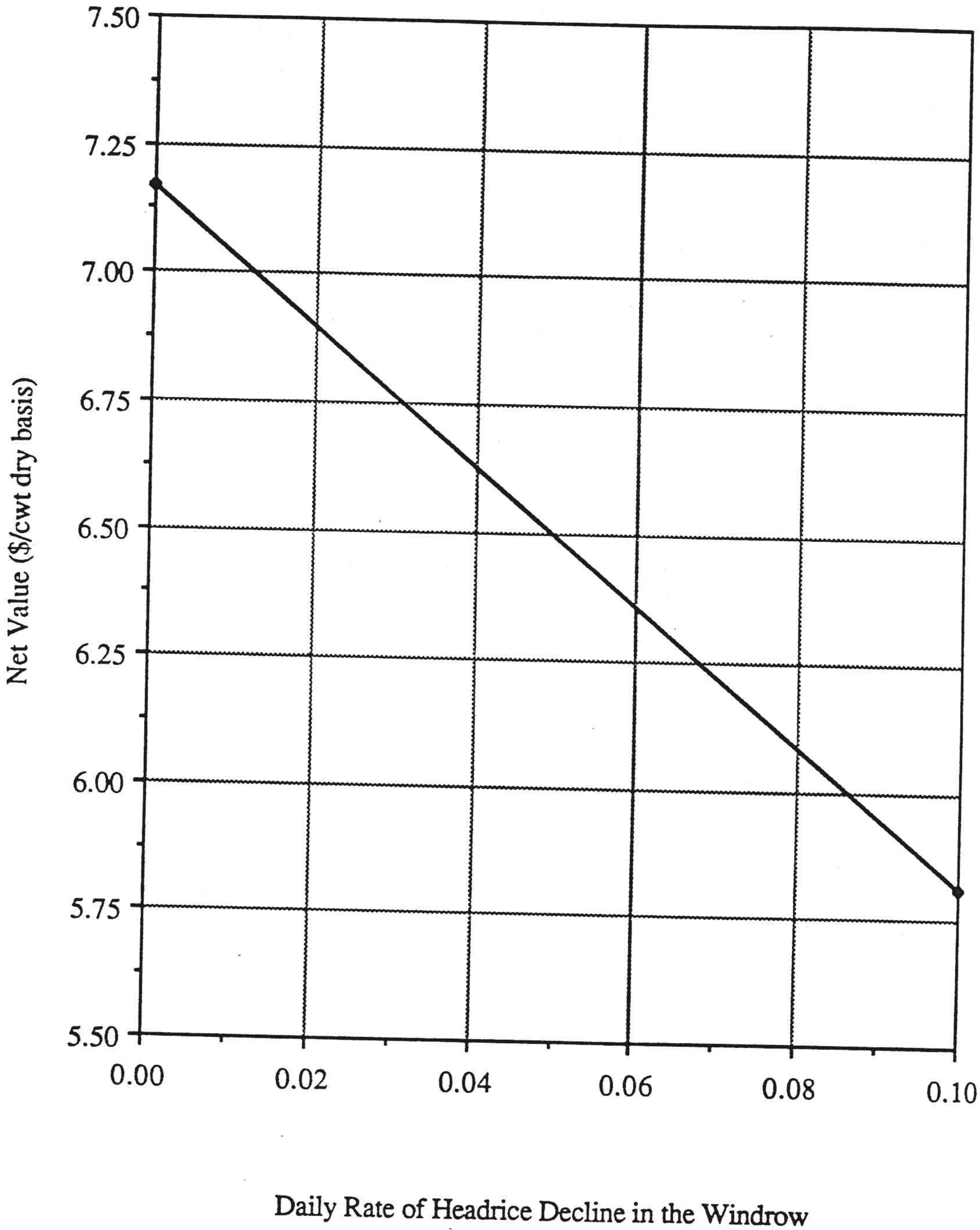


Figure 25. Decline in net grain value for increasing rates of head rice decline in the windrow with swath harvesting.