

## Swathing and Windrowing as Harvest Aids for Cuphea

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### ABSTRACT

**Cuphea** (*Cuphea viscosissima* Jacq. × *C. lanceolata* W.T. Aiton) is a potential new oilseed crop for temperate regions. Harvesting problems occur because current varieties are nondeterminate and shatter seeds. Because swathing may help overcome some of these problems, cuphea was swathed and allowed to dry in windrows for 0, 1, 2, 3, and 4 wk before combining. Measured variables at the time of combining were windrow weight, seed water content, seed yield, seed oil content, and post-swathing evaporation ( $E_{ps}$ ). Windrow weights decreased from about 40 to 14 Mg ha<sup>-1</sup> as combining was delayed until 3 wk after swathing. Weights decreased over time due to dehydration and leaf abscission, and they were associated hyperbolically with  $E_{ps}$ . Similarly, seed water content decreased from about 670 g kg<sup>-1</sup> at swathing to about 250 g kg<sup>-1</sup> at 30 mm  $E_{ps}$ . Seed shattering apparently was low as high yields were maintained each year until after at least 30 mm  $E_{ps}$ . Seed oil content was affected only slightly by delayed combining dates. Thus, swathing and windrowing cuphea and delaying combining until 30 mm  $E_{ps}$  substantially decreased the weight of material processed by the combine, reduced seed water content, but maintained high seed yields and seed oil contents.

FOR many recently domesticated seed crops, nondeterminate growth habit and propensity for seed shattering reduce harvesting efficiency and harvestable seed yields. At time of harvest, nondeterminate crops may support green leaves and stems, and their seeds can be at a wide range of maturities and moisture levels, all of which decrease efficient processing in modern harvesting equipment. Long-term solutions to these problems involve breeding varieties whose growth habits are determinate, mature plants dry rapidly, and ripened fruits retain seeds. With these traits crops can be left in the field to mature and dry naturally.

Unfortunately, breeding new varieties is costly and time consuming and, therefore, near-term solutions also are needed during the domestication of new crops. One near-term solution involves application of desiccants. When followed by direct combining, desiccants can reduce high plant moisture content at harvest and arrest the shattering process in ripening fruits. Another near-term solution involves swathing and windrowing followed by drying of windrows and then combining. Such harvesting alternatives are common for many partially or recently domesticated crops (e.g., Simpson, 1993; Thomas et al., 1991).

Cuphea (*Cuphea viscosissima* Jacq. × *C. lanceolata* W.T. Aiton) is a newly domesticated crop suffering from the aforementioned harvesting problems. Cuphea is of

interest because its seeds contain about 300 g kg<sup>-1</sup> oil, the preponderance of which is comprised of medium chain fatty acids (Graham et al., 1981; Thompson and Kleiman, 1988). Nearly all commercial medium chain fatty acids currently are derived from oils of coconut (*Cocos nucifera* L.) and palm kernel (*Elaeis guineensis* Jacq.), of which 600 000 Mg were imported into the USA and Canada in 2003 (FAOSTAT, 2005). Domestic supplies of such oils would be beneficial to North American agriculture, as well as industries that manufacture detergents, cosmetics, lubricants, hydraulic fluids, and confectionary products.

Although cuphea grows well in states such as Minnesota, up to half of seed production of Minnesota-grown cuphea is lost through shattering before and during direct combining operations (Gesch et al., 2005). Furthermore, directly combined seeds have water contents >400 g kg<sup>-1</sup> if harvested at times (late September to early October) when yield is maximized (Berti et al., 2005). Because stored seed must have water contents ≤100 g kg<sup>-1</sup> to preserve seed quality during long-term storage (personal observations), directly combined seeds must be dried. Seed drying incurs a separate time-consuming operation for producers, and it can be expensive, especially as energy costs continue to rise. Lastly, unless cuphea harvest is preceded by the application of a desiccant or a leaf-killing frost, harvested plants are turgid and support a dense green canopy of leaves. All of this wet material must be processed by the combine, and some of it inevitably contaminates the combine's seed hopper. Our objectives were to increase harvesting efficiency and decrease seed drying costs. Accordingly, we swathed and windrowed cuphea, and examined the effects of differing lengths of windrow drying time before combining on total windrow weight, seed water content, seed oil content, and seed yield.

### MATERIALS AND METHODS

Experiments were performed at the USDA-ARS Swan Lake Research Farm, Morris, MN, in 2004 and 2005. Seeds of PSR23 cuphea (Knapp and Crane, 2000) were sown in mid-May each year at a rate of 8 kg ha<sup>-1</sup>, at a soil depth of 1 cm, and at a row spacing of 61 cm. The total area sown each year was eight rows wide and 200 m long, but only small and homogenous sections of these areas were used for the swathing experiments. Soils were Barnes loams (Calcic Hapludoll, fine-loamy, mixed, superactive, frigid; with organic matter at 60 g kg<sup>-1</sup>, a bulk density of about 1.0 g cm<sup>-3</sup>, and a pH of 6.8). Fields had been plowed, field-cultivated (chiseled), and harrowed before sowing. Fertilizer was broadcast after sowing at rates of 70, 30, and 30 kg ha<sup>-1</sup> of N, P, and K, respectively. Weeds were controlled by herbicides: trifluralin [2,6-dinitro-*N,N*-dipropyl-4-(trifluoromethyl)benzenamine] applied preplant incorporated at 1 kg ai ha<sup>-1</sup>; and mesotrione

**Abbreviations:**  $E_{ps}$ , post-swathing evaporation; PM, Penman–Monteith equation.

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[2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione] applied postemergence at 0.1 kg a.i. ha<sup>-1</sup>. Cuphea has excellent tolerance to both herbicides (Forcella et al., 2005a). Herbicides were applied with a tractor-mounted sprayer that delivered 187 L ha<sup>-1</sup> at 207 kPa through a 3.1-m wide boom. Hand weeding supplemented chemical weed control.

As the crops matured, pairs of rows were swathed on 27 Sept. 2004 and 15 Sept. 2005. Plant stems were cut at 10 cm above the soil surface with a tractor-mounted sickle bar. The swathed material formed windrows, 1.3 m wide, which maintained their integrity over time because lateral branches of plants in the two paired rows were intertwined thoroughly.

The windrows were sectioned into 5-m long segments or plots. Plots were assigned to treatments through a completely random design in each year. Treatments were five drying periods: about 0, 1, 2, 3, and 4 wk after swathing. At each time period three or four randomly chosen plots (replicates) were processed individually as follows: (i) all plant material in a plot was rolled carefully onto a tarp and its fresh weight determined in the field; (ii) this material was fed into a stationary plot combine with screens fully open to minimize seed losses; (iii) crop residue was weighed after collection in a large bag fixed to the back of the combine; (iv) seeds plus chaff were collected from the hopper and weighed; (v) trash and seeds plus chaff were dried at 60°C for 1 wk to a seed water content of 55 g kg<sup>-1</sup> and weighed separately; and (vi) seed plus chaff samples were cleaned of chaff and weighed. Seed yields were calculated on the basis of 55 g kg<sup>-1</sup> of water in seeds. Oil contents of clean seed samples were determined using methods described by Forcella et al. (2005b).

Weather data were recorded at a permanent weather station located within 300 m of the experimental fields. These data were used to calculate cumulative evaporation from the day of swathing to combining ( $E_{ps}$ ). Potential evapotranspiration rates calculated for 2004 and 2005 were for a grass reference (short canopy, height = 0.12 m) using hourly weather data and the Penman-Monteith (PM) equation (Monteith, 1965) with the guidelines recommended by the American Society of Civil Engineers (Allen et al., 1998). Inputs for the PM method are solar radiation, air temperature, relative humidity, and wind speed.

The  $E_{ps}$  was related to weight losses of windrows, water losses of seeds, and seed yields. Differing mathematical functions were used to explore these relationships using regression and probability levels generated by Statistix Software (Tallahassee, FL). To describe losses of weight from windrows and losses of water from seeds due to  $E_{ps}$ , a hyperbolic loss equation was chosen, which is identical in form and analogous in function to the hyperbolic yield loss equation reported by Cousens (1985). A simple linear equation was chosen to describe seed yield loss due to shattering after exploration of a number of equations of differing forms. Regressions and ANOVA was used to explore differences among treatments and years in seed oil contents.

Lastly, to provide a simple economic perspective for the results on water losses from seeds, the Grain Drying Cost Calculator (Edwards, 2006) was used to approximate drying costs when water contents of freshly harvested seeds varied from 660 to 220 g kg<sup>-1</sup>. User-selected assumptions employed for such calculations included the use of a propane-heated, high-temperature, recirculating, grain drier with a 5 Mg h<sup>-1</sup> (250 bu h<sup>-1</sup>) capacity; a long-term storage seed water content of 100 g kg<sup>-1</sup>; and a minimal propane price of \$0.27 L<sup>-1</sup> (\$1 gal<sup>-1</sup>).

## RESULTS AND DISCUSSION

At the time of swathing, windrow weights were about 30 to 40 Mg ha<sup>-1</sup>, but dropped to 10 to 15 Mg ha<sup>-1</sup> after

2 wk of drying (Fig. 1A). When windrow weight loss from evaporation, leaf shed, etc., was compared against  $E_{ps}$ , data from both years showed nearly identical patterns (Fig. 1B). When aggregated across years, these data followed a hyperbolic weight loss function of the following form:  $W_e = W_i \times \{1 - [(r \times E_{ps}) / (1 + r \times E_{ps} / a)]\}$ , where  $W_e$  is windrow weight (Mg ha<sup>-1</sup>) after  $E_{ps}$  (mm of evaporated water),  $W_i$  is initial windrow weight (37 Mg ha<sup>-1</sup>), and  $r$  and  $a$  are proportional coefficients that describe maximum weight loss per millimeter of  $E_{ps}$  (0.05) and minimum residual windrow weight after infinite evaporation (0.9), respectively. The relationship was significant and had high attributable variability ( $p < 0.01$ ,  $r^2 = 0.89$ ).

Maximum seed water content averaged 660 g kg<sup>-1</sup> in 2004 and 670 g kg<sup>-1</sup> in 2005 and fell to values between 200 and 300 g kg<sup>-1</sup> within 2 wk (Fig. 1C). In each year the decline in seed water content (Fig. 1D) was related closely and similarly to  $E_{ps}$ . When aggregated across years, the data fit the following equation:  $M_e = M_i \times \{1 - [(r \times E_{ps}) / (1 + r \times E_{ps} / a)]\}$ , where  $M_e$  is seed water content (g kg<sup>-1</sup>) after  $E_{ps}$  (mm),  $M_i$  is initial seed water content (665 g kg<sup>-1</sup>), and  $r$  and  $a$  are proportional coefficients pertaining to maximum water loss per millimeter of  $E_{ps}$  (0.04) and minimum residual water content after infinite evaporation (1.1), respectively. The relationship was significant and had high attributable variability ( $p < 0.01$ ,  $r^2 = 0.95$ ).

Observed decreases in seed water content due to evaporation for 2 to 3 wk after swathing may impact drying costs considerably. The Grain Drying Cost Calculator (Edwards, 2006) indicated that the cost of propane use was a linear function of initial seed water content, with a slope of \$1.13 Mg<sup>-1</sup> of seeds. In other words, for every 10 g kg<sup>-1</sup> above 100 g kg<sup>-1</sup> of seed water (i.e., each percentage point above 10%), \$1.13 worth of propane must be used to dry each metric tonne of seeds. Consequently, allowing cuphea to dry in windrows for 2 to 3 wk (i.e., 670–200 g kg<sup>-1</sup>) could eliminate \$52 Mg<sup>-1</sup> in drying costs.

Overall, seed yields were similar both years. Maximum yields were 0.83 ( $\pm 0.15$ ) Mg ha<sup>-1</sup> in 2004 and 0.70 ( $\pm 0.05$ ) Mg ha<sup>-1</sup> in 2005. As combining was delayed, a trend for decreasing seed yields was apparent both years (Fig. 1E). Seed losses presumably resulted from shattering while plants dried in windrows.

The relationship of seed yield with  $E_{ps}$  (Fig. 1F) was linear and did not differ between years ( $p > 0.05$ ), but it was characterized by high variability. When data were aggregated across years, the resulting equation was: seed yield (Mg ha<sup>-1</sup>) = 0.71 – 0.0032  $\times E_{ps}$  ( $p < 0.01$ ,  $r^2 = 0.28$ ). Although attributable variability was low, this equation summarizes the fact that average seed losses of windrowed cuphea of >0.1 Mg ha<sup>-1</sup> were not apparent until after 30 mm of elapsed evaporation after swathing, or about 2 wk of drying. Thus, seeds were retained in windrowed plants at least as long as, if not longer than, the time and  $E_{ps}$  (30 mm) required to lower windrow weights and seed water contents to levels at which high harvest efficiencies would be expected.

Overall seed oil content was higher in 2004 than 2005 (290 vs. 260 g kg<sup>-1</sup>; ANOVA,  $p < 0.01$ ). Seed oil content

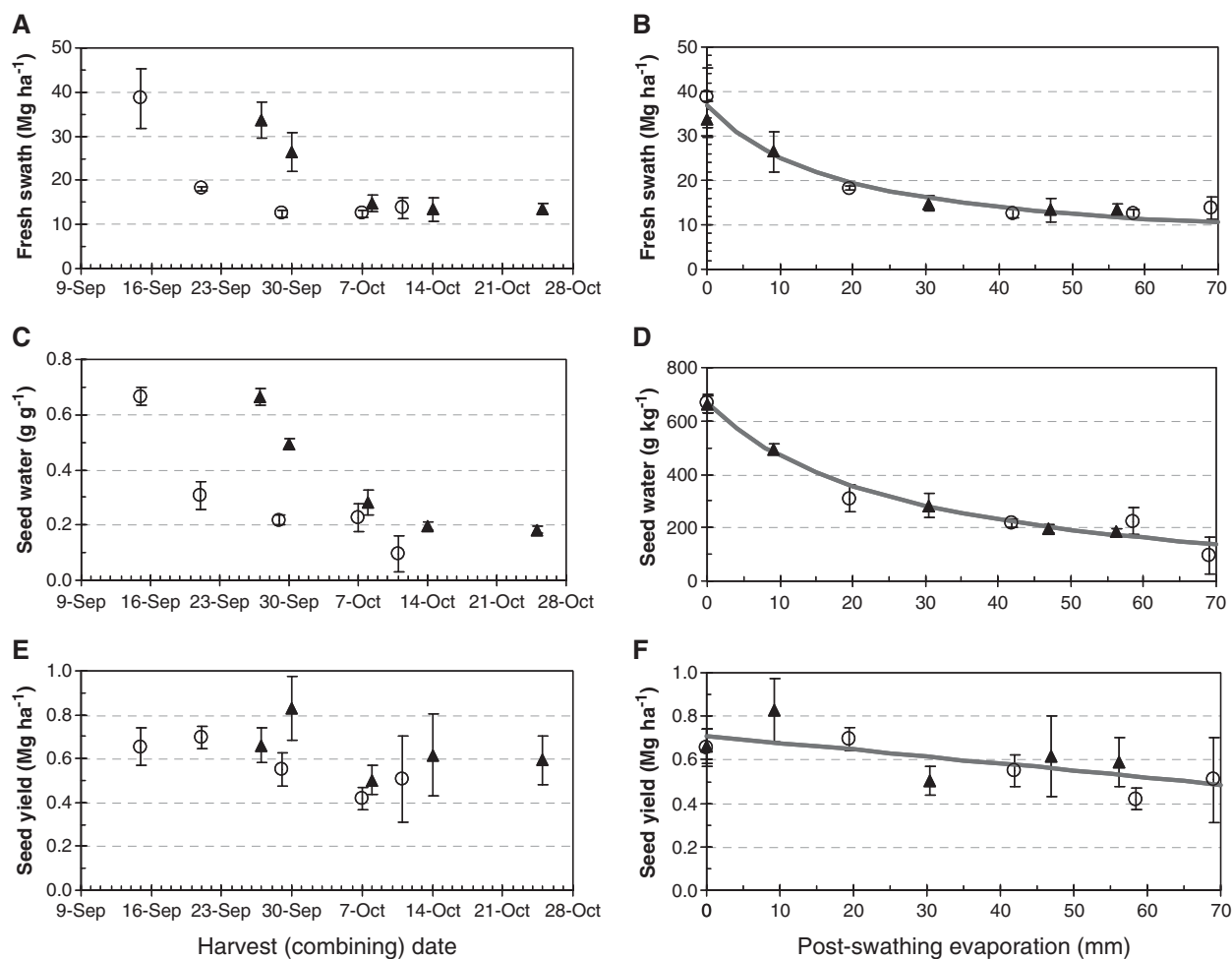


Fig. 1. (A, B) Fresh weights, (C, D) seed water contents, and (E, F) seed yields of swathed cuphea plants as affected by (A, C, E) time or (B, D, F) evaporation accrued after swathing during 2 yr, 2004 (triangles) and 2005 (circles). Seed yields are based on a seed water content of  $55 \text{ g kg}^{-1}$ . Swathing occurred on 27 Sept. 2004 and 15 Sept. 2005. Symbols and bars represent mean values  $\pm$  one standard deviation unit above and below the means.

may be related inversely with air temperature during seed fill (Forcella et al., 2005b). During the last 2 wk before swathing, only 96 degree-days (base  $10^\circ\text{C}$ ) were accumulated in 2004 compared to 131 degree-days in 2005. In 2004, average oil content for the first three harvest dates was  $300 \text{ g kg}^{-1}$ , which was higher ( $p = 0.03$ ) than that for the last two dates ( $270 \text{ g kg}^{-1}$ ). In 2005, however, harvest date did not influence oil content ( $p > 0.1$ ). In summary, harvesting cuphea 2 wk (or  $30 \text{ mm } E_{ps}$ ) after swathing did not affect seed oil content, and harvesting cuphea after longer periods either had no effect or reduced seed oil content only modestly.

Previous research showed that highest seed yields occurred when cuphea was harvested directly by combine in mid- to late September in western Minnesota (Gesch et al., 2005). Our new results allow preliminary conclusions and recommendations for harvesting PSR23 cuphea in northern latitudes after swathing. These conclusions and recommendations are as follows: (i) swath and windrow cuphea in mid- to late September; (ii) allow windrows to dry until occurrence of at least  $30 \text{ mm}$  cumulative  $E_{ps}$ , which typically is at least 2 wk in western Minnesota during late September; (iii) at that time more than 60% of the weight of windrows will have been lost

through evaporation and leaf shed, which means less mass of material passing through the combine and less energy required for processing by the combine; (iv) water content of seeds will decrease after  $30 \text{ mm}$  evaporation by more than 60%, from 670 to about  $250 \text{ g kg}^{-1}$ , which lessens postharvest drying costs considerably (seed water content must be  $\leq 100 \text{ g kg}^{-1}$  for long-term storage); and (v) seed losses in windrows are low until at least after  $30 \text{ mm}$  cumulative  $E_{ps}$ .

Comparisons of directly combined and swathed canola (*Brassica napus* L.) often showed no advantage for either system in terms of harvested seed yield (e.g., Thomas et al., 1991). However, swathing PSR23 cuphea and harvesting 2 wk later potentially can reduce greatly the amount of crop mass that must be processed by a combine, as well as the water content of harvested seeds. Furthermore, this procedure will not sacrifice yield or oil content, seeds will be relatively dry, and less cuphea stem and leaf mass need be processed by the combine.

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