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Optimizing Swathing and Chemical Desiccant Timing to Accelerate Winter Carinata Maturation

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ABSTRACT

Brassica carinata (carinata) is an emerging dedicated oilseed feedstock for 'drop-in' biofuels and renewable bioproducts. There is great potential for carinata to be produced as a winter crop providing economic and environmental benefits in the Southeast United States. The indeterminate flowering of carinata produces pods of different maturity making it difficult to determine the optimum harvest time. The objective of this study was to determine the effects of harvest aid and application timing on crop maturation, seed and oil yields, and fatty acid composition. *B. carinata* was evaluated in a 2-yr field study at NFREC, Quincy, FL, during the 2014–2015 and 2015–2016 growing seasons. Treatments were initiated when seed moisture was at 501 to 558 g kg^{-1} and continued at 7 d intervals for 4 wk. In 2015, harvesting at 21 d after physiological maturity (DAPM) produced 28% greater yield than earlier harvest dates while in 2016, harvesting at 14 DAPM or later produced 31% greater yields than earlier harvests. Swathing reduced seed yield by 11% relative to control in 2015, however, no differences occurred in 2016. Seed shattering increased with maturation regardless of harvest aid and was greatest at 21 DAPM. The use of a harvest aid 14 to 21 DAPM, when seed moisture is <285 g kg^{-1} and more than 80% of the seeds have changed color, would accelerate the transition to summer crops by 7 to 14 d. These results indicate the potential of harvest aids to accelerate seed dry-down and uniformity thereby facilitating the timely planting of subsequent summer crops.

Core Ideas

- *Brassica carinata* is an emerging dedicated oilseed feedstock for 'drop-in' biofuels.
- Sequential flowering produces a mixture pods of different maturity.
- Harvest aids enhance seed maturation, crop dry down with little effect on yield.
- Applying harvest aid 14 to 21 d after physiological maturity when seed moisture is <28.5% accelerate transition to summer crops by 7 to 14 d.

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Carinata (*Brassica carinata* A.Braun) is a C3 species that originated in the Ethiopian highlands and derived by the interspecific hybridization of *B. nigra* L and *B. oleracea* L. (Warwick, 2011). This crop is currently produced during the summer season in Canada and the Northern Plains of the United States (J. Klingenberg, personal communication, 2018). However, in the Southeast United States there is great potential for carinata to be produced as a winter crop providing economic and environmental benefits (Seepaul et al., 2016). This new dedicated industrial oilseed crop is grown for its oil content with favorable chemical composition to produce 'drop in' aviation fuels (ARA, 2017). It's superior agronomic traits, drought and heat tolerance (Malik, 1990), pod shatter resistance (Banga et al., 2011), non-dormancy, and fit into current agricultural infrastructure for harvesting, handling, storage, transportation, processing, etc. have positioned carinata for commercialization within the United States (D. Wright and J. Klingenberg, personal communication, 2018). Commercial winter carinata production occurred on 4000 ha in the tristate region of Alabama, Florida and Georgia for the past 3 yr. Scaling up production to meet an increasing demand for sustainably produced oilseed feedstock requires integrating carinata into existing and diverse crop rotations.

In the Southeast United States, the crop is planted in November and harvested from early-May to early June (Seepaul et al., 2016). Carinata self-defoliates with the onset of reproductive development as photoassimilates and nutrients are translocated from leaves to the developing seed with complete leaf abscission at physiological maturity (PM). Low seed shattering in carinata allows the crop to be directly combined. However, indeterminate flowering in carinata results in a mix of mature, partially mature, immature, and unfilled pods that makes it difficult to determine the optimum harvest time. This physical admixture reduces the harvest maturity and uniformity of seed moisture concentration. Moreover, the fibrous carinata stems which can stay green for several weeks after the seed is mature limits the speed and efficiency of direct combining. Therefore, cost effective and optimized methods to

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Abbreviations: PM, physiological maturity; DAPM, days after physiological maturity.

accelerate maturity and achieve uniform seed and stem ripening for mechanized harvesting may be desirable for producers.

Harvest aids accelerate harvest maturity through seed desiccation and chlorophyll degradration of vegetative biomass (Gubbels et al., 1993b) and facilitate mechanical harvesting. Chemical desiccation using contact herbicides such as paraquat dichloride disrupts cell membrane integrity, resulting in rapid tissue dehydration at the point of contact with subsequent degradation of adjacent tissues. Another approach to aid harvest maturity is swathing, followed by natural dehydration in windrows, a practice common in canola production (Cenkowski et al., 1989; Vera et al., 2007). Cutting the plants below the first reproductive branch terminates the translocation of nutrients to the developing seed followed by rapid chlorophyll degradation in the seeds and stem tissues.

Fatty acid synthesis and oil deposition changes during *B. napus* seed development (Onemli, 2014; Vera et al., 2007), generally increasing as the seeds mature (Vera et al., 2007). Seed glucosinolate concentration also increase by translocation to seeds on maturation. Glucosinolates are nitrogen- and sulfur-containing secondary metabolites involved in biotic and abiotic stress tolerance (del Carmen Martínez-Ballesta et al., 2013). Application and timing of a harvest aid may have an effect on seed yield and quality of oilseed brassicas (Vera et al., 2007).

Chemical desiccants and swathing have been effectively used in several grain crops including lentils (*Lens culinaris* L.) (Tang et al., 1992), canola (*Brassica napus* L.) (Esfahani et al., 2012;Vera et al., 2007), faba beans (*Vicia faba* L.) (Betts and Morrison, 1980) and flax (*Linum usitatissimum* L.) (Gubbels et al., 1993a, 1993b). While both methods are fast acting, the efficacy of contact desiccants depend on the type of chemical used, concentration, temperature, humidity, day length, light intensity, and degree of plant coverage. In both approaches the treated crop is allowed to dry for multiple days, depending on weather conditions, before combining.

For both harvest aid approaches, application timing should be optimized to minimize loss of seed yield and oil quality (Brown et al., 1999; Vera et al., 2007). Therefore, the objectives of this study were to (i) determine the optimum time to desiccate or swath carinata and (ii) determine the effects of swathing and desiccation on carinata seed and stem dry down, seed yield and oil quality.

MATERIALS AND METHODS

Site Characterization, Experimental Design, and Management

Non-irrigated field trials were conducted during the 2014–2015 and 2015–2016 winter–spring growing seasons at the University of Florida North Florida Research and Education Center (30°32'44"N, 84°35'40.7"W), Quincy, FL, on a Dothan sandy loam (fine, loamy siliceous thermic Plinthic Kandiudults). Carinata variety 110994EM sourced from Agrisoma Biosciences Inc., Gatineau, QC, Canada) was planted using a Hege 1000 series cone planter (Wintersteiger Inc., Salt Lake City, UT) in 17.8 cm rows at a rate of 6.1 kg ha^{-1}. Plots were 1.5 × 6.1 m with 1.8 m between plots. In both years, alleys were planted with carinata and mowed at PM to reduce border and alley effects.

Nitrogen fertilizer was applied at a rate of 94 kg ha^{-1}, with 15% preplant incorporated, 43% topdressed at bolting and 43% topdressed at flowering. Potassium and P was preplant incorporated at 42 and 84 kg ha^{-1}, respectively. Sulfur was applied 10 kg ha^{-1}, 50% at bolting and 50% at flowering. In 2015, significant freeze damage resulted in replanting on 9 Jan. 2015 with PM reached on 13 May, 2015. In 2016, carinata was planted on 16 Nov. 2015 reaching PM on 26 Apr. 2016. Pendimethalin (Prowl) was applied as a preemergent herbicide at planting at an active ingredient rate of 0.73 L ha^{-1} in both years. Diflubenzuron (Dimilin 2L) applied at active ingredient rates of 0.05 L ha^{-1} was tank mixed with Spinosad (Tracer) at 0.10 L ha^{-1} active ingredient and applied on 14 Apr. 2015 to control diamond back moths (*Plutella xylostella* L). Bifenthrin (Bifenture) was applied at active ingredient rates of 0.05 L ha^{-1} to control aphids and diamond back moths on 7 Jan. 2016.

The early season mean air temperature differed between study years and the 30-yr average. End of season temperature in April, May, and June was relatively similar and compared well with the 30-yr average. Total precipitation for the growing season from 9 Jan. 2015 to 10 June 2015 and 12 Nov. 2015 to 25 May 2016 was 520 and 1520 mm, respectively (Table 1).

The experimental design was a randomized complete block, two-way factorial with four harvest timings and three harvest aid treatments–two harvest aids and a non-treated check. Physiological maturity was determined when >70% of pods in the upper third of the canopy turned green to yellowish green or light brown with seeds ranging from green to olive green to light yellow similar to *B. napus* (Elias and Copeland, 2001). At PM (0 DAPM), entire plots were either swathed at a 30.5 cm stubble height or sprayed with paraquat dichloride (Parazone 3SL) at an active ingredient rate of 0.63 L ha^{-1} tank mixed with an NIS adjuvant (Agri Dex at 0.47 L 378.5 l^{-1}). Treatments were applied 0, 7, 14, and 21 DAPM. Treated carinata plants were allowed to naturally dry in the field for 7 d followed by threshing at 7, 14, 21, and 28 DAPM according to the calendar dates in Table 2.

Data Collection

Entire desiccated and swathed plots were threshed with a MODEL SCM-0100 bundle thresher (HyTech, Southern Alberta, Canada). Seeds were oven-dried at 50°C for 72 h to determine plot yield. Seed loss was measured by counting the seeds captured in two 0.25 m^2 trays per plot after harvest.

Seed moisture concentration at harvest was determined gravimetrically using a 15-g sample from hand-threshed pods harvested from the top, middle, and bottom of the canopy and combined. Moisture content of oven-dried seeds was used to correct yield to 8% moisture content. Stems from five plants were sampled on each harvest date, weighed fresh, oven dried at 55°C for 72 h to determine stem moisture concentration at harvest. Seed moisture content and test weight of treated plots were measured with a Steinlite Sl95 moisture meter (Steinlite, Atchison, KS) using ~0.75 kg seeds. Two samples of 1000 seeds were randomly subsampled and weighed. Total glucosinolates, protein content, oil content, and fatty acid composition were predicted using near infrared reflectance spectroscopy (NIRS). Samples were analyzed using a FOSS XDSTM Rapid Content Analyzer

Table 1. Total precipitation, mean air temperature, and the 30-yr average by month for 2014–2015 and 2015–2016 winter–spring growing season in Quincy, FL.

	Total precipitation			Mean air temperature		
Month	2014–2015	2015–2016	30-yr avg	2014–2015	2015–2016	30-yr avg
	mm			°C		
Oct.	81	7	65	19.1	20.3	19.5
Nov.	145	171	75	11.1	18.3	14.4
Dec.	271	175	98	12.6	16.6	11.4
Jan.	138	150	68	10.1	9.4	10.2
Feb.	88	89	132	9.2	11.8	11.6
Mar.	60	73	106	17.4	17.3	15.3
Apr.	153	480	114	21.1	18.9	18.6
May	75	50	67	23.3	22.4	22.8
June	143	157	128	25.6	25.8	25.8
Total	1154	1352	853			

Table 2. Harvest aid application and harvest dates (Julian days in parentheses) during the 2015 and 2016 harvest seasons in Quincy, FL.

	2015		2016	
DAPM	Treatment date	Harvest date	Treatment date	Harvest date
0	13 May 2015 (133)	13 May 2015 (133)	27 Apr. 2016 (118)	27 Apr. 2016 (118)
7	13 May 2015 (133)	20 May 2015 (140)	27 Apr. 2016 (118)	4 May 2016 (125)
14	20 May 2015 (140)	27 May 2015 (147)	4 May 2016 (125)	11 May 2016 (132)
21	27 May 2015 (147)	3 June 2015 (154)	11 May 2016 (132)	18 May 2016 (139)
28	3 June 2015 (154)	10 June 2015 (161)	18 May 2016 (139)	25 May 2016 (146)

Table 3. Analysis of variance for harvest aid and application timing fixed effects on seed yield, seed loss, seed moisture, stem moisture, 1000 seed weight, test weight, oil concentration, and oil yield of carinata harvested at Quincy, FL, in 2015 and 2016.†

Fixed effect	DFn	Seed yield	Seed loss	Seed moisture	Stem moisture	1000 seed weight	Test weight	Oil concentration	Oil yield
		kg ha^{-1}	kg ha^{-1}	g kg^{-1}	g kg^{-1}	g	kg hL^{-1}	g kg^{-1}	L ha^{-1}
2015									
HA	2	12.92***	55.65***	206.9***	94.83***	13.74***	1.09	0.29	11.75***
AT	4	40.89***	17.18***	352.72***	10.64***	15.61***	14.72***	4.88**	39.34**
HA × AT	6	2.21	5.12***	14.59***	0.67**	1.76	1.13	0.34	1.75
2016									
HA	2	0.43	21.6***	42.57***	368.26***	5.32**	21.44***	0.39	0.46
AT	4	12.36***	12.75***	436.81***	59.77***	13.71***	1.95	3.0*	11.33***
HA × AT	6	0.29	4.44**	9.11***	16.88***	0.87	2.02	0.58	0.39

† DFn, numerator degrees of freedom; HA, harvest aid; AT, application time.

* F value significant at the 0.05 probability level. ** F values significant at the 0.01 probability level. *** F values significant at the 0.001 probability level.

(FOSS Inc., Eden Prairie, MN). Sample spectra were evaluated using the ISIscan program (FOSS Analytical, Hilleroed, Denmark) using a proprietary carinata calibration (Agrisoma Biosciences, Inc.), including numerous calibration and validation samples. The proprietary prediction model developed by Agrisoma Biosciences utilized nuclear magnetic resonance spectroscopy (Oxford MARAN Ultra Benchtop NMR System, Oxford Instruments, Oxfordshire, UK) as well as gas chromatography (Agilent 6890N, Agilent Technologies, Santa Clara, CA) to develop the underlying equation (Taylor et al., 1992)

Statistical Analysis

Each year's data was analyzed separately by fitting mixed models with repeated measures using PROC MIXED in SAS (SAS Institute Inc., Cary, NC). Harvest aid and application timing and their interactions were considered fixed effects while replication was considered a random effect. Application timing was considered as a repeated measure and responses were evaluated at the 0.05 probability level. For the repeated measure, a first order autoregressive covariance was used, and the denominator degrees of freedom for the Type III F-test were adjusted with the Satterthwaite method. Differences among harvest aids and application timing were separated using the PDIFF option in PROC MIXED procedure. Correlations among seed yield, loss, moisture, stem moisture, seed weight, oil, protein, and glucosinolate concentrations, oil yield and fatty acid concentration were determined by correlation analysis (PROC CORR) on the combined 2015 and 2016 data. When correlations were detected, regressions were performed using PROC REG in SAS to quantify the relationship.

RESULTS AND DISCUSSION

Carinata Yield Response to Harvest Aid and Timing

There was no harvest aid × application timing interaction ($P = 0.08$), however, harvest aid ($P < 0.0001$) and application timing ($P < 0.0001$) main effects existed for seed yield (Table 3). In 2015, averaged across harvest aid, harvesting at 21 DAPM resulted in 28% greater yield than earlier harvest dates while in 2016, harvesting at 14 DAPM or later resulted in 31% greater

Table 4. Effect of harvest aid and timing of application (DAPM†) on carinata seed yield grown in 2015 and 2016 winter–spring, Quincy, FL.

Application timing (DAPM)	Seed yield			
	Control	Desiccation	Swathing	Mean
	kg ha^{-1}			
	2015			
0	1768.2			1768.2 c‡
7	1977.2	1714.8	1751.1	1814.4 c
14	2502.3	1834.1	1837.2	2057.9 b
21	2705.3	2531.9	2482.4	2573.2 a
28	2781.3	2780.9	2405.9	2656.0 a
Mean	2346.9 A	2215.4 AB	2119.2 B	
	2016			
0	2081.8			2081.8 b
7	2266.2	2016	1807.7	2030.0 b
14	2787.1	2885.3	2662.9	2778.4 a
21	3114.9	3212.8	3182.9	3170.2 a
28	2980.3	3091.5	2994.3	3022.0 a
Mean	2646.1 A	2801.4 A	2662 A	

† DAPM, days after physiological maturity.

‡ Within column, means followed by the same lowercase letters, and within rows, means followed by the same uppercase letters are not different (P > 0.05) using PDIFF option in PROC MIXED.

yields than earlier harvests (Table 4). When averaged across harvest aid, yields were similar between chemical desiccation and swathing in both years. However, relative to the non-treated control, swathing reduced yield by 11% in 2015 while no differences occurred among treatments in 2016 (Table 4). The efficacy of harvest aids may depend on the weather conditions and the stage of crop development (Vera et al., 2007). Both seasons received adequate precipitation throughout the growing season; however, the distribution of the precipitation across critical stages of development were different between seasons. In the drier and warmer 2015 season, seed yield was limited primarily by the later planting date and reduced precipitation during the flowering and pod development stages relative to 2016.

Seed Loss

Seed shatter during harvest varied with harvest time, as indicated by a significant harvest time × harvest aid interaction ($P = 0.0001$) in both years (Table 3). This reflected the difference between harvest aids at different application timing over both years. Seed shattering increased with maturation regardless of harvest aid and reached its maximum level by 21 DAPM in both years (Table 5). Averaged across application timing, chemical desiccation increased seed loss by 41 (5.3 kg ha^{-1}) and 84% (8.3 kg ha^{-1}) relative to the non-treated control in 2015 and 2016, respectively. Swathing increased seed shattering loss further by 65 (9.1 kg ha^{-1}) and 92% (9.2 kg ha^{-1}) in the two study years (Table 5). Across all treatment combinations, maximum seed loss (36.3 kg ha^{-1}) occurred when carinata was swathed at 28 DAPM in 2016 at < 6% seed moisture. This was lesser than the 39 to 70 kg ha^{-1} reported for diverse brassica species under low shattering conditions (Gan et al., 2008). Seed shattering after maturity in brassica oilseed crops can result in significant yield losses as high as 50% if harvesting is delayed (Price et al., 1996) especially during hot and dry environments at the time of harvest. As a shatter tolerant species (Wang et al., 2007), carinata may be desiccated or swathed with comparatively minimal seed loss.

Table 5. Carinata seed loss variation in response to harvest aid and timing of application (DAPM†) in 2015 and 2016 winter–spring, Quincy, FL.

Application timing (DAPM)	Seed loss		
	Control	Desiccation	Swathing
	kg ha^{-1}		
	2015		
0	0 c‡		
7	4.6 bcC	8.5 bB	16.7cA
14	7.7 bcC	10.3 bB	18.8 bcA
21	9.9 abB	14.4 abB	26.0 abA
28	16.4 aB	18.8 aB	27.0 aA
	2016		
0	0 b		
7	0 bB	1.8 cA	1.8 bA
14	1.3 bB	5.5 bcA	7.6 bA
21	3.2 aC	13.2 abB	30.5 aA
28	3.5 aC	19.0 aB	36.3 aA

† DAPM, days after physiological maturity.

‡ Within column, means followed by the same lowercase letters, and within rows, means followed by the same uppercase letters are not different (P > 0.05) using PDIFF option in PROC MIXED.

Seed, Stem Moisture Concentration, and Seed Color

Seed moisture and seed color change are morphological indicators of PM in brassicas (Elias and Copeland, 2001) and can be used to determine optimum time to desiccate or swath (Vera et al., 2007). Harvest aid and application time interactions had an effect on seed and stem moisture concentration in both years ($P < 0.0001$) (Table 3). In 2015, both harvest aids reduced seed moisture relative to control across all application timing while in 2016, the response varied among treatments (Table 6). Relative to the desiccated carinata, swathing did not reduce seed moisture after 7 DAPM in 2015 and was effective at 7 and 14 DAPM during 2016 (Table 6). Delaying harvest aid application increased seed yield, evident from the strong negative correlation between seed yield and seed moisture ($r = -0.63$, $P < 0.0001$; $y = -2.9419x + 3021.9$, $R^2 = 0.43$).

Seed moisture is a reliable indicator of seed maturation. Reduction in seed moisture declined incrementally as the seed matured. Compared to the control, averaged across years, swathing reduced seed moisture by 37, 52, 37 and 37% at 7, 14, 21, and 28 DAPM, respectively. This was more effective than desiccation-induced seed moisture reduction by 19, 27, 11 and 15 percentage points at 7, 14, 21, and 28 DAPM (Table 6). Natural seed dehydration progressed rapidly during the 28 d period from 501 to 169 g kg^{-1} in 2015 and 558 to 58 g kg^{-1} in 2016 (Table 6) even though precipitation totaled 13.8 cm (2015) and 15.4 cm (2016) during this period. The average temperature during this maturation phase was relatively stable in both years (24.1 ± 1.3°C in 2015 and 22.1 ± 2.2°C in 2016). In 2015, seed dry down during the 28 d maturation period was 1.2% per day while in 2016 it was 1.8% per day in the non-treated carinata. Increased seed dehydration in 2016 may have resulted from the lower relative humidity during the 28 d maturation period in 2016 (77.8%) than in 2015 (83.1%). Relative humidity was

Table 6. Effect of date of harvest aid and application timing (DAPM†) on carinata seed and stem moisture concentration t at harvest in 2015 and 2016, Quincy, FL.

Application timing	Seed moisture content at harvest			Stem moisture content at harvest		
(DAPM)	Control	Desiccation	Swathing	Control	Desiccation	Swathing
	g kg^{-1}					
	2015					
0	500.9 a‡			623.0 a		
7	368.8 bA	231.0 aB	184.0 aC	580.0 abA	591.1 aA	240.0 aB
14	247.8 cA	172.2 bB	152.3 b B	565.0 abA	462.2 bA	163.8 abB
21	194.5 dA	140.2 cB	116.7 cB	504.6 bA	435.4 bcA	116.3 bB
28	168.5 eA	127.6 cB	105.8 cB	380.6 cA	382.9 cA	90.0 bB
	2016					
0	558.1 a			717.9 a		
7	441.7 bA	431.3 aA	328.3 aB	739.5 aA	663.9 aB	112.3 aC
14	285.6 cA	227.6 bB	102.3 bC	624.0 bA	522.1 bB	90.1 bC
21	90.4 dA	68.7 cA	62.2 cA	511.1 cA	299.8 cB	64.8 cC
28	57.6 eA	49.2 cA	36.6 cA	412.5 dA	161.3 dB	65.6 cC

† DAPM, days after physiological maturity.

‡ Within column, means followed by the same lowercase letters, and within rows, means followed by the same uppercase letters are not different ($P > 0.05$) using PDIFF option in PROC MIXED.

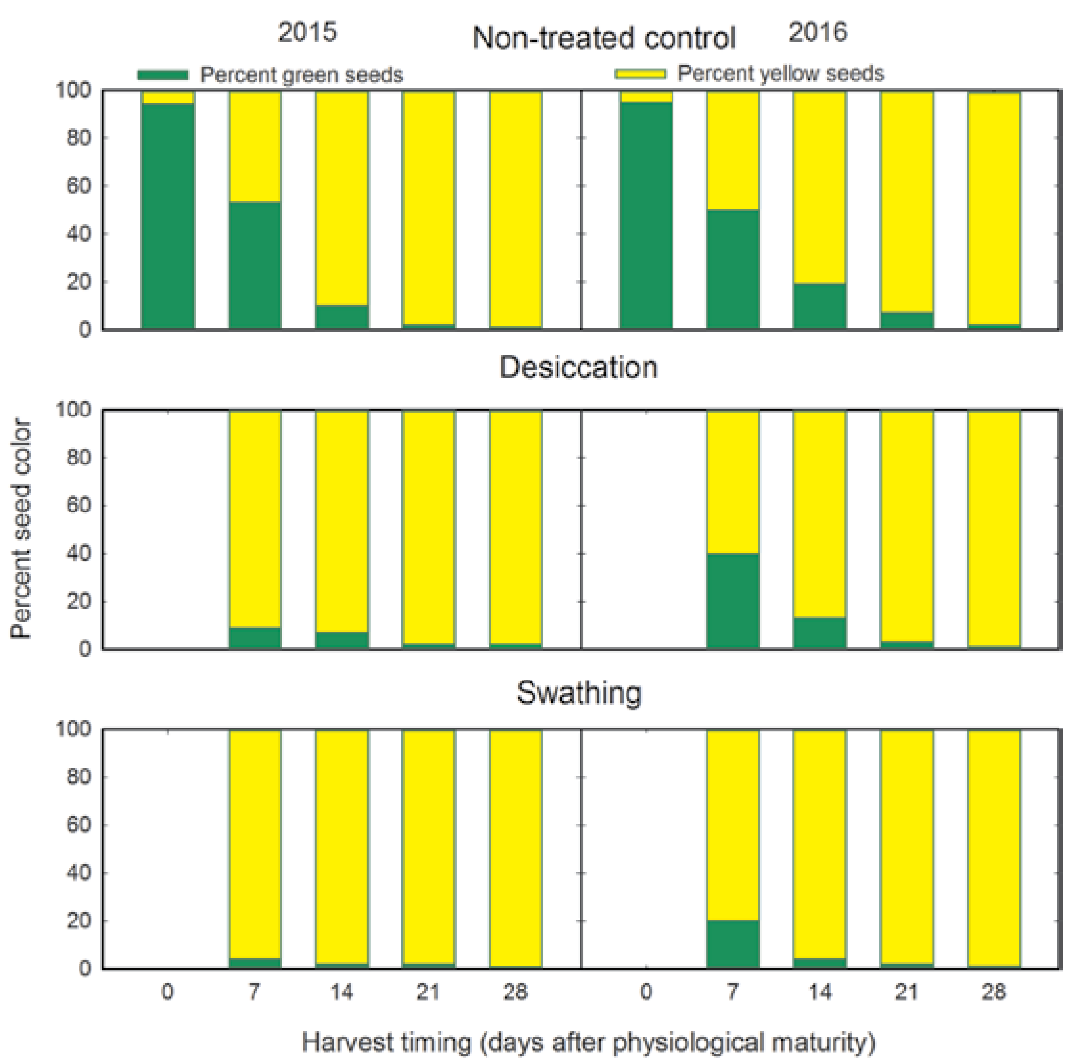

Fig. 1. Progression of seed color change with harvest aid at carinata harvest during the 2015 and 2016 harvest seasons, Quincy, FL.

Table 7. Effect of date of harvest aid and application timing (DAPM†) on carinata 1000 seed weight and test weight in 2015 and 2016 winter–spring, Quincy, FL.

Application timing (DAPM)	1000 Seed Weight				Test weight			
	Control	Desiccation	Swathing	Mean	Control	Desiccation	Swathing	Mean
	g				kg hL^{-1}			
				2015				
0	4.6			4.6 b	63.1			63.1 c‡
7	5.4	4.8	4.5	4.9 b	68.0	69.1	69.3	68.8 a
14	5.5	5.2	5.1	5.3 a	69.6	69.3	69.1	69.3 a
21	5.5	5.2	5.3	5.3 a	68.1	69.1	68.5	68.6 a
28	5.4	5.2	5.2	5.3 a	66.8	66.8	63.9	65.8 b
Mean	5.3 A	5.1 B	5.0 B		67.1	68.6	67.7	
				2016				
0	3			3.0 c	61.2			61.2
7	4	3.4	3.5	3.6 b	63.6	66.4	63.2	64.4
14	3.9	3.7	3.7	3.8 ab	63.3	67.2	67.6	66.0
21	4.1	3.8	4	4.0 a	62.0	68.3	68.3	66.2
28	4	4	3.9	4.0 a	62.7	68.1	66.8	65.9
Mean	3.8 A	3.7 A	3.8 A		62.6 B	67.5 A	66.5 A	

† DAPM, days after physiological maturity.

‡ Within column, means followed by the same lowercase letters, and within rows, means followed by the same uppercase letters are not different ($P > 0.05$) using PDIFF option in PROC MIXED.

below 75% on 5 vs. 11 of the 28 d period in 2015 and 2016, respectively.

Stem moisture varied with harvest aid and application timing, as indicated by a significant interaction between these effects in both years ($P < 0.0001$). Relative to the control, chemical desiccation reduced stem moisture in 2016 only, while swathing was effective in both years across all application timings (Table 6). The effectiveness of harvest aid treatments depends on the moisture content at the time of application. In 2016, desiccation or swathing at 21 and 28 DAPM reduced stem but not seed moisture concentration. In naturally dehydrated carinata, the waxy tough fibrous stems remained green at 28 DAPM in both years even though seed moisture decreased with time. This may complicate direct combining since green stems are difficult to cut and can plug combines, forcing operators to reduce harvesting speed. Reduction in stem moisture concentration occurred at a slower rate than seed moisture concentration in both years (Table 6). Harvest aids that result in rapid reduction in stem moisture concentration will have a similar effect on reducing seed moisture evident from the correlation between stem and seed moisture concentration ($r = 0.83$, $P < 0.0001$; $y = 1.252x + 129.26$; $R^2 = 0.68$).

Associated with seed maturation is a change in seed coat color. After 14 DAPM, >80% of seeds changed from green to olive green or yellow in the non-treated carinata (Fig. 1). As the plant matured (after 7 DAPM), both harvest aids reduced green seeds <4%. The proportion of green seeds was less in swathed than desiccated treatments, due primarily to the rapid chlorophyll clearing during the hot and dry treatment periods. Green seeds in carinata harvests would primarily affect seed storage rather than oil quality. Feedstock quality of carinata oil remains unaffected with the presence of high levels of chlorophyll unlike rapeseed where chlorophyll concentration reduces food grade oil quality (Daun, 1982).

For safe seed storage, carinata has to be at 10% seed moisture or less. If moisture is greater than 10%, seeds can be dried with forced air at low temperatures or air dried. Seed moisture concentration of swathed carinata was 3–5% less than desiccated carinata across both years. Although seed color at 14 DAPM was uniform (>90% yellow seeds) in the treated carinata, the harvest aids did not reduce the seed moisture during the 7 d dry down period after treatment across all application timing in 2015 and 7 and 14 DAPM in 2016. Depending on the weather conditions during the maturation period in any given year, longer durations after the application of a harvest aid may be necessary to dry carinata seeds <10% for safe storage. Producers may also need to monitor the seed dry down process by subsampling seeds from the top, middle, and bottom of the canopy before deciding to harvest carinata.

Seed Weight

Seed weight, a key yield component in oilseed crops, varied with harvest time ($P < 0.0001$) and harvest aid ($P < 0.0001$) in both years (Table 3). Maximum seed weight occurred at 14 DAPM, however, heavier seeds were produced in 2015 (Table 7). Both harvest aids reduced 1000 seed weight from 5.3 to 5.1 g in 2015 but not in 2016, averaging 3.8 g. Temporal variation in seed weight may be related to the seasonal variation in in climate factors (temperature, precipitation) during flowering and pod set with the drier and warmer 2015 producing heavier seeds. Test weight, a measure of seed bulk density, increased from 0 to 28 DAPM in 2015 but was similar across all application timings during 2016. Lower test weight at 0 DAPM indicates that the crop was not mature and produced shrunken seeds on drying. Regardless of harvest aid treatment, test weight increased by 7% over the non-treated carinata in 2016.

Oil Concentration and Oil Yield

Oil concentration and oil yield varied with application timing in both years ($P < 0.05$) while oil yield differed with harvest aid main effects only in 2015 ($P < 0.0001$) (Table 3). Similar to seed yield, greater oil concentration and oil yield occurred in the wetter year of 2016 across all application timings (Table 8). Seed oil concentration progressively increased reaching a maximum

Table 8. Effect of date of harvest aid and application timing (DAPM†) on carinata oil concentration and yield in 2015 and 2016 winter–spring, Quincy, FL.

Application timing (DAPM)	Oil concentration				Oil yield			
	Control	Desiccation	Swathing	Mean	Control	Desiccation	Swathing	Mean
	g kg^{-1}				l ha^{-1}			
				2015				
0	353.8			353.8 c‡	676.9			676.9 c
7	358.7	349.7	349.9	352.8 c	767.2	648.4	666.0	693.9 c
14	358.6	359.1	359.7	359.1 b	971.4	712.8	716.0	800.1 b
21	364.0	362.3	360.5	362.3 b	1064.9	991.8	962.3	1006.3 a
28	372.6	369.8	368.9	370.4 a	1084.4	1082.9	960.1	1042.5 a
Mean	361.5	360.2	359.8		913.0 A	859.0 AB	826.1 B	
				2016				
0	412.4			412.4 c	937.9			937.9 c
7	454.9	435.7	435.1	441.9 b	1131.0	949.9	851.1	977.3 c
14	463.3	448.5	451.0	454.3 a	1403.1	1398.7	1300.6	1367.5 b
21	441.4	459.9	449.7	450.3 a	1494.3	1596.5	1549.4	1546.7 a
28	456.6	447.8	454.0	452.8 a	1464.7	1499.0	1471.1	1478.3 a
Mean	445.72	447.975	447.45		1286.2	1361.0	1293.1	

† DAPM, days after physiological maturity.

‡ Within column, means followed by the same lowercase letters, and within rows, means followed by the same uppercase letters are not different ($P > 0.05$) using PDIFF option in PROC MIXED.

Table 9. Analysis of variance for harvest aid and application timing fixed effects on glucosinolate, protein and seed oil fatty acid concentrations of carinata harvested at Quincy, FL in 2015 and 2016.†

Fixed effect	DFn	Glucosinolate	Protein	Palmitic C16:0	Stearic C18:0	Oleic C18:1	Linoleic C18:2	Linolenic C18:3	Eicosenoic C20:1	Erucic C22:1
		ug g^{-1}	g kg^{-1}							
2015										
HA	2	16.78	1.45	1.15	0.12	0.52	0.39	0.33	1.2	1.87
AT	4	12.91***	25.15***	6.76***	85.57***	3.61*	39.61***	54.18***	14.36***	29.28***
HA × AT	6	0.18	0.19	7.14***	1.3	1.4	1.98	3.05*	3.41**	0.51
2016										
HA	2	1.89	21.31***	19.82***	5.87**	11.85***	5.43**	2.35	9.91***	7.01
AT	4	15.54***	18.50***	11.57***	14.21***	22.03***	19.93***	5.78**	46.2***	23.71***
HA × AT	6	1.61	2.47	5.55***	3.27*	6.58***	1.94	1.77	5.55***	3.45

† DFn, numerator degrees of freedom; HA, harvest aid; AT, application time.

* F value significant at the 0.05 probability level. ** F values significant at the 0.01 probability level. *** F values significant at the 0.001 probability level.

Table 10. Effect of date of harvest aid and application timing (DAPM†) on carinata glucosinolate and protein concentration in 2015 and 2016 winter–spring growing season, Quincy, FL.

Application Timing (DAPM)	Glucosinolate concentration				Protein concentration			
	Control	Desiccation	Swathing	Mean	Control	Desiccation	Swathing	Mean
	ug g^{-1}				g kg^{-1}			
				2015				
0	124.7			124.7 bc‡	309.4			309.4 c
7	126	122.6	118.4	122.3 c	341.8	341.5	336.6	340.0 b
14	129	127.3	122.4	126.2 b	357.1	354.4	350.7	354.1 a
21	129.5	125.7	123.7	126.3 b	359.9	352.9	355.6	356.1 a
28	134.6	131.8	127.2	131.2 a	365.7	364.2	357.2	362.4 a
Mean	128.8	126.9	122.9		346.8	353.3	350.0	
				2016				
0	64.6			64.6 c	257.0			257.0 b
7	84.8	84.7	74.8	81.4 b	264.8	246.4	250.9	254.0 b
14	84.9	81.7	84.6	83.7 b	265.8	252.4	261.9	260.0 b
21	91.4	83.7	88.1	87.7 a	285.2	262.6	269.8	272.5 a
28	87.6	88.9	86.1	87.5 a	275.5	271.2	260.9	269.2 a
Mean	82.7	84.8	83.4		269.7 A	258.2 B	260.9 B	

† DAPM, days after physiological maturity.

‡ Within column, means followed by the same lowercase letters, and within rows, means followed by the same uppercase letters are not different ($P > 0.05$) using PDIFF option in PROC MIXED.

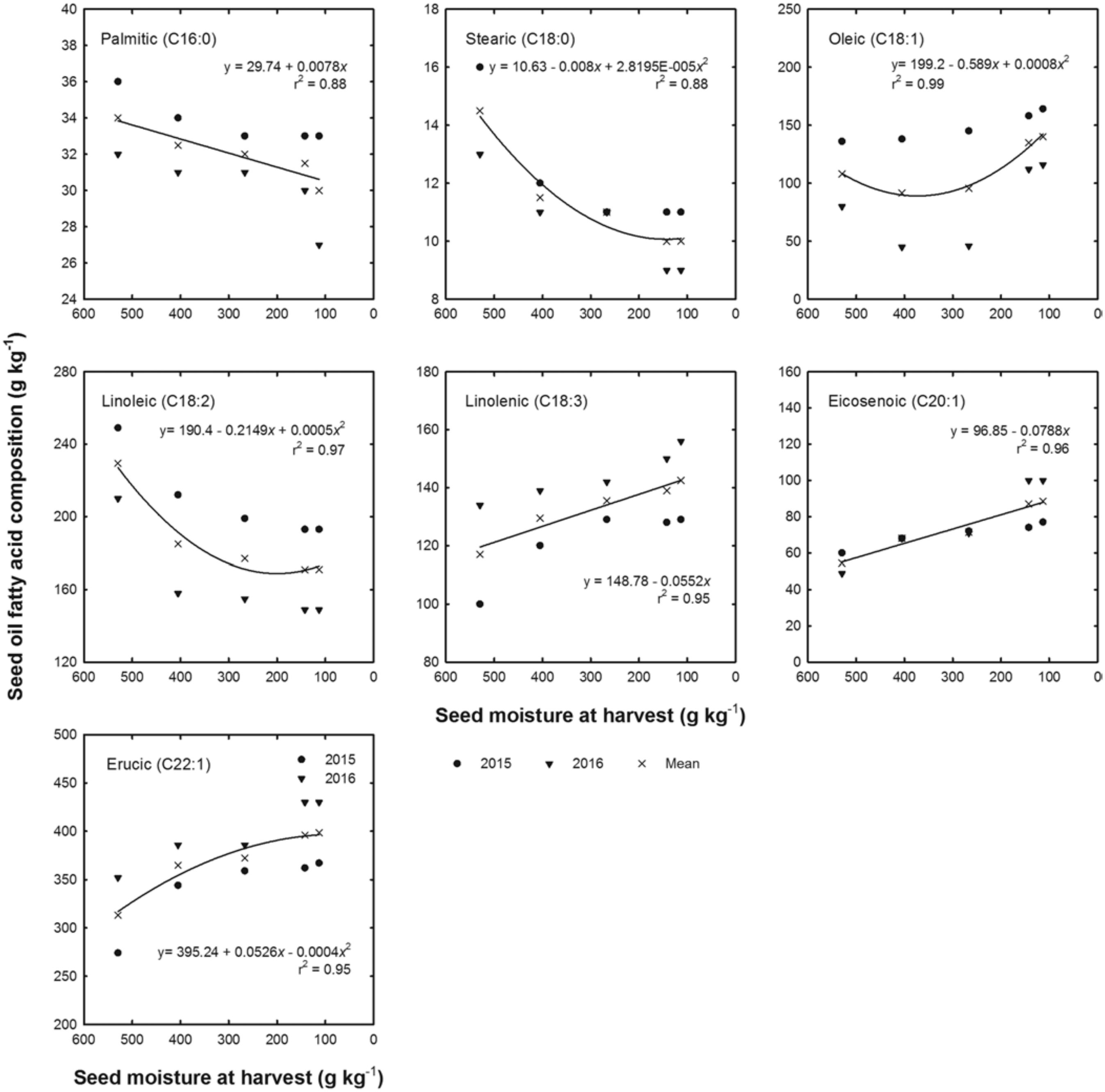

Fig. 2. Changes in carinata fatty acid concentration with seed moisture concentration (maturation) at the time of harvest aid application during the 2015 and 2016 harvest seasons. The symbols are measured fatty acid concentration and regression lines are fitted to the mean of 2015 and 2016 results using linear or quadratic functions.

at 28 DAPM in 2015 and 14 DAPM in 2016 (Table 8). Trends in oil yield were similar between years with maximum oil yield produced at 21 DAPM. Seed yield ($r = 0.95$, $P < 0.0001$; $y = 0.5659x - 297.05$, $R^2 = 0.91$) and oil concentration ($r = 0.57$, $P < 0.0001$; $y = 0.0419x + 301.97$, $R^2 = 0.27$) accounted for 99 and 31% of the variation in oil yields, respectively.

Glucosinolate and Protein Concentrations

Glucosinolates are secondary metabolites translocated from the roots, leaves, and stems to the developing seed with a primary role in plant defense against herbivores and pathogens. Total glucosinolates varied with application timing only ($P < 0.0001$, Table 9), with seeds accumulating maximum concentrations at 28 and 21 DAPM in 2015 and 2016, respectively (Table 10).

The high protein low fiber press cake is a valuable co-product of carinata oil that can be used as a supplement in ruminant nutrition (Rodriguez-Hernandez and Anderson, 2018). Protein concentration varied with harvest aid in 2016 ($P < 0.0001$) and application timing in both years ($P < 0.0001$) (Table 9). The accumulation of protein was greatest at 14 and 21 DAPM in 2015 and 2016, respectively (Table 10). Relative to the control, the use of a harvest aid in 2016 reduced protein concentration by 5% (Table 10).

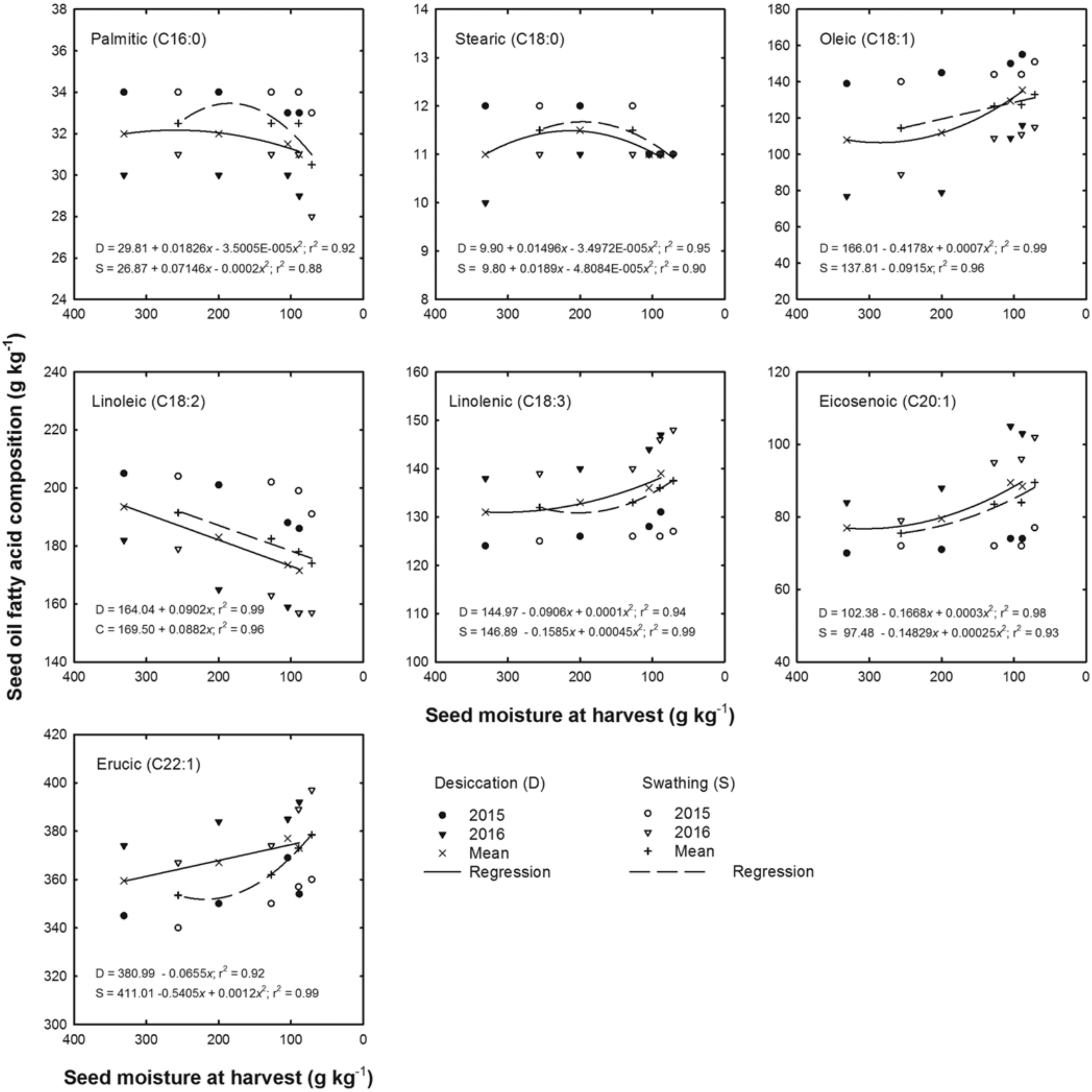

Fig. 3. Changes in carinata fatty acid concentration with seed moisture concentration (maturation) 7 d after desiccation (solid symbols) or swathing (open symbols) during the 2015 and 2016 harvest seasons. The symbols are measured fatty acid concentration for each harvest aid and regression lines are fitted to the mean of 2015 and 2016 results using linear or quadratic functions.

Fatty Acid Accumulation

Carinata seed oil fatty acid composition varied with harvest aid in 2016 only, and with timing of harvest aid application in both years ($P < 0.05$) (Table 8). Averaged across years, the distribution of fatty acids in g kg^{-1} ranked C18:0 (11.4), C16:0 (32.0), C20:1 (73.9), C18:1 (114.0), C18:3 (132.7), C18:2 (186.7), and C22:1 (369.0). As the seed matured with simultaneous decline in seed moisture concentration, C16:0, C18:0, and C18:2 levels decreased with concomitant increases in C18:1, C18:3, C20:1, and C22:1 levels (Fig. 2) similar to compositional trends in canola (Vera et al., 2007). Levels of C22:1, a desirable long chain monounsaturated fatty acid that allows for greater oil to jet fuel conversion efficiency, was similar across harvest aids averaging 349 and 386 g kg^{-1} in 2015 and 2016, respectively. Our results suggest that delaying the application of a harvest aid until seed moisture is 200 g kg^{-1} will increase C22:1 concentration (Fig. 1).

The trends in fatty acid accumulation 7 d after harvest aid treatment were similar to the accumulation of fatty acids at the time of application. Seven days after desiccation or swathing, C16:0, C18:0, and C18:2 levels decreased while C18:1, C18:3, C20:1, and C22:1 concentrations increased similar in trends to non-treated carinata (Fig. 3). Delaying the harvest aid application may have extended the maturation phase of seed development facilitating greater conversion of photoassimilates to seed storage lipids, starch and proteins, evident from the increased seed weight, oil, and protein concentrations with delayed treatment timing (Tables 7, 8, and 10).

Carinata is primarily produced as a spring annual in Canada and Northern Plain States (J. Klingenberg, personal communication, 2018). Mild winters in the Southeast United States allow carinata to be double cropped as a winter crop (D. Wright, personal communication, 2018). However, commercial production as a winter annual in the Southeast United States may be risky partly due to freeze injury during vegetative and reproductive stages of development during intensely cold years, high incidence of pests and diseases during warm years, while wet springs can delay harvest or increase fusarium head blight. Agrisoma and UF are currently developing early maturing cultivars that are tolerant to cold temperatures. Current production recommendations for North Florida is mid-November, which minimizes the freeze injury to the crop. In 2015, two separate hard-freeze events (16 h from 18–19 Nov. 2014 and 25 h from 8–9 Jan. 2015) resulted in significant stand mortality resulting in replanting of the study. Since 2016, considerable improvements in cultivar selection for frost injury availed the new and improved commercial variety, Avanza 641.

CONCLUSION

Winter carinata production in the US Southeast require agronomic management tools to accelerate carinata uniform maturity to allow timely land preparation and planting of summer row crops. When time is not a limiting factor, carinata can be allowed to naturally dry down and directly combined. Our results suggest that desiccating or swathing carinata would enable a gain of 7 to 14 d, depending on weather conditions, to transition to summer crops. However, harvest aids require an additional field operation, which will increase cost of production. Although the yields from swathing did not differ from desiccation during the two study years, field weathering, pre-germination, seed discoloration, breakdown of oils and opportunistic pod diseases during wet springs can further reduce yield and seed quality rendering swathing too risky for the Southeast (Tang et al., 1990). The decision to use a harvest aid will depend on the economics of an additional field operation and the possibility of increasing seed loss from shattering.

These results indicate the potential of chemical desiccants and swathing to accelerate seed dry-down and uniformity of seed maturity of winter carinata thereby facilitating the timely planting of summer crops in the Southeast United States. The use of a harvest aid 14 to 21 DAPM, when seed moisture is <285 g kg^{-1} and more than 80% of the seeds have changed color, would allow a gain of 7 to 14 d to transition to summer crops. When crop termination is timed at the optimum phenological stage and adjusted for environmental conditions year-to-year, the use of harvest aids will produce yields similar to naturally dehydrated carinata with little or no effect on the protein, oil, and fatty acid concentration. Carinata is highly shatter resistant with <1.5% loss under risky conditions (low seed moisture). The 7-d dry-down period post treatment in this study resulted in uniform maturation but did not effectively reduce seed moisture content >10% and may require longer periods for maximum efficacy. While swathing may be risky due to erratic weather, chemical desiccation prior to direct combining is an effective tool to accelerate maturation uniformity and harvest in the Southeast United States.

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