EVALUATION OF FLAX AND OTHER COOL-SEASON OILSEED CROPS FOR YIELD AND ADAPTATION IN TEXAS

A Dissertation

by

MURALI KRISHNA DARAPUNENI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2012

Major Subject: Agronomy

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ABSTRACT

Evaluation of Flax and Other Cool-Season Oilseed Crops for Yield and

Adaptation in Texas. (August 2012)

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Finding the alternate biofuel feedstock(s) in addition to and/or replacement of traditional soybean feedstock is necessary to meet the future demand of biofuels. Two field studies were conducted in diverse environments in Texas during 2007-2011 to evaluate the yield, adaptation, and oil content of 4 cool-season crop species (rapeseed, safflower, flax, and camelina). In addition to the evaluation of yield and adaptation in these cool-season crops, two more studies were conducted during 2009-2011 to study flax yield components (field study) and the effect of vernalization and photoperiod on flowering of flax (growth chamber study). Out of two field studies conducted in Texas, the evaluation of four cool-season crops was designed as a randomized complete block with fifty-one genotypes (four species) and three replications in nine locations across the Texas. In addition to the evaluation of cool-season crops, an exclusive replicated study was conducted in flax to evaluate 20 genotypes for the yield, adaptation, and association between yield and its components in three locations in South Texas. Additionally, a growth chamber study was setup as a split-split plot design with twenty genotypes, two vernalized treatments (vernalized and unvernalized), and two photoperiods (10 hours and 14 hours).

Spring rapeseed (canola) and safflower were the highest yielding crops with a maximum yield of 1372 kg ha^{-1} and 1240 kg ha^{-1}, respectively. In South and Central Texas, fall -

seeded flax yield averaged 1075 kg ha^{-1} with a mean oil content of 38.3 %. The flax genotype evaluation in Southeast Texas suggested that all genotypes developed in Texas showed relative cold tolerance compared to genotypes developed in other locations. A cross between Caldwell / Dillman (Texas genotype) was highly adapted to the environments of southeast Texas. Nekoma and York (genotypes developed in North Dakota) yielded well in non-cold years (> -2°C) in College Station. Overall, flax is well adapted to growth in the area surrounding College Station, TX. The results of association of yield and its components in flax suggest that tiller number was the most significant contributing factor ($p<0.05$) affecting yield of flax in all three locations. However, the effect of tiller number was almost negated by the effect of pods per tiller (compensatory) in two out of three locations. The effect of vernalization and photoperiod on flowering of 20 genotypes of flax suggested that Texas genotypes delayed anthesis for 7 days or more in non-vernalized seedlings. These genotypes also delayed anthesis for 12 days or more in vernalized and short day conditions compared to vernalized and long day conditions. In summary, the spring rapeseed in diverse environments of Texas and fall-planted flax in South Texas showed promising yield and adaptation. Selection for more productive tiller number and intrinsic earliness of flowering to reduce the time of maturation would benefit the flax yields in Southeast Texas. Safflower was widely adapted to Texas and with increased oil content could have potential to the biofuel industry in Texas.

DEDICATION

This dissertation is dedicated to my dear wife (Vijaya Bathina) and son (Shrihan Darapuneni), my parents (Chennaiah Darapuneni and Chennamma Darapuneni), and my brothers (Rama Krishna Darapuneni and Hari Krishna Darapuneni).

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

By the end of 2012, the global consumption of crude oil and petroleum products is estimated to be about 90 million barrels per day (United States Energy Information Administration, 2011). This will continue to increase as the worldwide population continues to grow. At this rate, it is projected that the extractable deposits of fossil fuels will be exhausted in 2050 (BP Review of World Energy, 2007).

The United States is a leading nation in energy consumption with a current crude oil and petroleum demand of about 19 million barrels per day (21% of total world consumption). Consumption is expected to reach 22 million barrels per day by 2035 (United States Energy Information Administration, Annual Energy Outlook 2011 National Energy Modeling system). The current total U.S. consumption is composed of 50% from the U.S. domestic supply and the remaining 50% (9 million barrels per day) is imported from the other nations, predominantly Middle Eastern countries. This purchase of foreign oil comprises about 50% of the U.S. trade deficit. It is estimated that the annual imported value of petroleum and crude oil products is about 268 billion dollars (United States Energy Information Administration, Annual Energy Outlook 2011). Finding alternative renewable resources for exhausting fossil fuels and acquiring energy independence are key issues of national energy security for the United States.

Apart from the various renewable energy resources, ethanol and biodiesel (agriculture based) have rapidly evolved into important biofuel supplies in U.S. with the current

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This dissertation follows the style of Industrial Crops and Products.

contributions of 7.5% and 0.35% of the total fuel supply respectively (United States Energy Information Administration, 2009). However, the expansion of the biodiesel industry will require the identification of suitable feedstocks that maximize the production capacity and economical feasibility.

Significant research has been directed to plant-derived biofuel oils and advanced enzymatic technology for the conversion of carbon sources to biofuels. However, the selection of a feedstock crop for these renewable biofuel methods is often challenging and requires thorough investigation.

1.1. Important biodiesel crops around the world

Various edible oilseed crops that are currently utilized for biodiesel production include soybean (*Glycine max (L.) Merr.*), palm (*Elaeis guineensis*), and rapeseed (*Brassica napus L.*); while many other non-edible oilseed crops such as castor (*Ricinus communis L.*), pongamia (*Pongamia pinnata (L.) Pierre.*), calophyllum (*Calophyllum inophyllum L.*), and jatropha (*Jatropha curcas L.*) have been evaluated for potential biodiesel feedstock use (Gressel, 2007).

In the U.S., the testing of several biofuel feed stock crops in different adaptive regions has been conducted and numerous trials are in progress to supplement the predicted future feedstock demand. The current research focuses primarily on the evaluation of flax and other cool-season oilseed crops such as rapeseed (canola), safflower, and camelina for biofuel production in the different agro-climatic regions of Texas.

1.2. Background of evaluated crop species

1.2.1. Origin, production regions, and uses of Rapeseed

Rapeseed is believed to have originated in Europe or North America (Becker et al., 1995). Canola (*Brassica napus L.*) is a collective term applied to improved varieties of rapeseed with low erucic acid (<2%) and low glucosinolate (<30 micromoles/gram of meal) contents

(Bell, 1993). Rapeseed contains about 40% oil content compared to 20% in current major oil producing crops in like soybean and cotton. The composition of canola oil is very favorable for cooking purposes due to its low saturated fats (7%) and long chain carbon (22), which contribute to excellent stability. Canola oil has high levels of mono (oleic acid) and poly unsaturated fats, which are desirable for human consumption (Buntin et al., 2010). Buntin et al., (2010) also reported that rapeseed meal was rich with protein (38% crude protein) and crude fiber (11%).

North Dakota led the U.S. production of rapeseed and contributed more than 90 percent of total U.S. production in 2011 (USDA-NASS, 2011). A recent survey suggested increased interest in canola production in the Southern Great Plains, especially in Oklahoma with 37,200 ha under canola production in 2011 (USDA-NASS survey report, 2011).

1.2.2. Origin, production regions, and uses of Safflower

Safflower (*Carthamus tinctorius*) is an annual crop that originated in Mediterranean region over 4000 years ago (Chapman and Burke, 2007). Safflower oil is a good source of both monosaturated (oleic acid) and polysaturated (linoleic acid) fatty acids, depending upon the variety. High linoleic oil can be used as a drying agent in paints and varnishes because of its non-yellowing characteristic. The meal, which is rich with protein (24 percent) and high in fiber, is used as a protein supplement for livestock and poultry feed. Safflower seed is also commonly used in wild and domestic bird feed.

Safflower is grown worldwide for seed production, especially in India, the United States, and Mexico (Food and Agriculture Organization, 2009). India leads the world in safflower production with 189,000 metric tons of seed production, followed by the United States (109,756 metric tons) (Food and Agriculture Organization, 2009). In the United States, safflower is mainly grown in the cereal growing Western Great Plains region, including California, North Dakota, Montana, Utah, and South Dakota (Berglund et al., 2007). In 2011, California was the leading state in safflower production with 51,000 hectares followed by Utah with 23,000 hectares (USDA-NASS, 2011). Safflower is widely adapted

to semi-arid and arid environments of the U.S. because of the considerable tolerance to severe drought and heat (Kephart et al., 1990). It is believed that the long tap- root (up to 3 m) contributes most to the drought and heat tolerance of safflower.

1.2.3. Origin, production regions, and uses of Camelina

Camelina cultivation was assumed to begin in the Neolithic and Iron Ages (Putnam et al., 1993) as an oil-supplying crop (Knorzer, 1978). Ehrenstng and Guy (2008) suggested more specifically that the camelina originated from Finland to Romania and east to the Ural Mountains. However, other authors believed that camelina originated in the Mediterranean to Central Asia (Putnam et al., 1993). Camelina monocultures were found in the Rhine River Valley as early as 600 BC. It was shown to be cultivated from Rome to southeastern Europe and the Southwestern Asian steppes (Knorzer, 1978).

Camelina is also known as false flax, linseed dodder, or gold-of-pleasure. Camelina can germinate in the temperatures as low as -11°C (EM-8953 E publication, 2008). Camelina is a short-seasoned (85 to 100 days) crop, currently grown in numerous mid-western U.S. climates.

Camelina is comparable to flax in quality with similar protein content and elemental composition, with the exception of a higher sulfur content and hence one of its common names false flax (Robinson, 1987). Putnam et al. (1993) reported that the oil content of camelina ranged from 29 to 39% depending upon the variety, and was comparable to soybean meal, containing 45 to 47% crude protein and 10 to 11% fiber (Korsrud et al., 1978). Camelina is widely used in the poultry industry, in feeding wild or caged birds (Fogelfors, 1984; Mabberly, 1987). Camelina oil is also used as a replacement for petroleum oil in pesticide sprays (Robinson and Nelson, 1975).

1.2.4. Origin, production regions, and uses of flax

Flax (*Linum usitatissimum* L.) is one of the oldest cultivated crops and originated in the Mediterranean and Southwest Asia regions (Millam et al., 2005). Hettiarachchy et al. (1990) reported that flax is rich with proteins (26.9-31.6%), lipids (31.9 to 37.8%, dry weight basis), and dietary fiber (36.7 to 46.8%). Flax also contains a variety of essential Omega-3-fatty acids predominantly linolenic acid, oleic acid, and linoleic acid. Flax, being rich in "lignans", also proved to have anti-carcinogenic properties (Lay et al., 1989). It can be used as an ingredient in designer foods, as it contains numerous essential nutrients besides anti-cancer compounds (Stitt, 1990). In addition to the various health benefits, flax also can be used in the manufacturing of paper, plastic, and numerous derived industrial products (Domier et al., 2000). However, the yield potential and oil content also make flax a viable candidate as a biofuel crop.

Extensive research conducted in early and mid 1900's established flax as a potential cash crop in the U.S., particularly in the states like North Dakota, South Dakota, and Minnesota (Berglund, 2002). The major flax producing countries include Canada, China, and India. Canada was a leading nation in flax production in 2007 with about 34% of total world production, followed by China with a contribution of 25.5% (FAO, 2009). The United States was the fourth largest producer of flax with about 8% (150,000 metric tons) of total world seed production (FAO, 2009). Due to increasing interest in biofuels, flax is being considered as a potential biofuel crop in the U.S. and other regions of the world.

1.3. Genotype evaluation in flax

The productivity and yields of flax depend on the diversity in genetic contribution and the interaction between the genotype and the environmental conditions (El-Hariri et al., 1994). It was also found that the significant differences were observed among flax cultivars concerning straw, seed yield, oil content, and components (El-Hariri et al., 1994, 2002, and 2004).

Identifying appropriate genetic material for a particular region is essential for genotype selection and crop improvement. This task can be often established by conducting preliminary yield and agronomic trials, especially if the species is new to the environment. The preliminary yield trials with limited selection of existing genotypes creates an opportunity to identify the potential parental sources for future breeding ventures, but also aids in the development of proper agronomic practices necessary to maximize yield. Extending the research to multiple locations following preliminary yield testing develops an understanding of genotype and environmental interactions. The adaptation and performance of the different genotypes of a specific crop depends on the selection of a genotype for a specific trait of interest and environmental conditions for which it is bred. The effective partitioning of environmental interactions among different genotypes also creates an opportunity for a breeder to accurately classify them under different adaptive regions. For example, the accurate classification of winter and spring grown flax based on their environmental adaptation could determine certain agronomic management practices (planting date, optimum application of fertilizers, prediction of biotic and abiotic stresses) to follow for that particular region.

1.4. Management practices in flax

1.4.1. Seeding rate and row spacing

Studies suggest that the yield of flax is largely affected by seeding rate, row spacing, and weed pressure (Gubbels and Kenaschuk, 1989; Lafond, 1993). Further research revealed that increasing the seeding rate tends to decrease the weed competition, thus aiding in achieving better yields in flax (Robinson, 1949; Gruenhagen and Nalewaja, 1969). In the absence of weeds, the response of seed yield to seeding rate was largely variable depending on the different environmental conditions (Gruenhagen and Nalewaja, 1969; Gubbels and Kenaschuk, 1989; Lafond, 1993; Stevenson and Wright, 1996). The decrease in row spacing of 15 cm did not affect the seed yield of flax either in weedy or weed free conditions (Alessi and Power, 1970; Stevenson and Wright, 1996).

1.4.2. Factors affecting emergence of flax

Kurt (2001) concluded that the emergence of flax was highly dependent on the genotype, seedbed conditions, cultivated treatments, and their interactions. Temperature showed significant effect on the emergence of flax, where the highest emergence occurred at 30°C (87%) and the lowest at 10°C (Kurt and Bozkurt, 2006).

Orhan and Bokurt (2006) studied the effect of temperature and photoperiod on seedling emergence of flax under controlled environment. They indicated that the emergence of flax was highest and fastest at 30°C temperature. A photoperiod treatment of 12h dark and 12h day time had highest emergence. However, the effect of photoperiod on the emergence of seedling and rate of emergence was not significant. Overall, the effect of temperature on the seedling emergence was higher than the photoperiod.

1.4.3. Impact of nitrogen fertilizer on flax

In most cases, application of nitrogen should enhance the seed yield of flax (MacIssac et al., 1941; Molberg, 1961; Prasad and Biswas, 1954). It was also reported that higher nitrogen application rates could result in significant yield loss due to luxurious weed growth, if weeds are not managed appropriately (Culbertson, 1961). Molberg (1961) indicated that nitrogen placed in close proximity to the seed at the time of planting decreased seed germination significantly and negatively affected seed yield. The oil content and iodine value were significantly reduced at higher nitrogen application (Dybing, 1964).

A study conducted at the University of Minnesota suggested that the application of 90 kg ha^{-1} N resulted in 1758 kg ha^{-1} seed yield compared to 1098 and 420 kg ha^{-1} at 45 and 0 kg ha^{-1} N applications, respectively (Flax institute of United States, 1957). An experimental study conducted at Beeville and Kernes, TX showed that application of 50 kg ha^{-1} of N resulted in better yield (1198 and 834 kg ha^{-1}, respectively) compared to 0, 17, 34, and 67 kg ha^{-1} N applications (Gipson et al., 1961). Similar research results (on average 683 kg ha^{-1} of yield at 50 kg ha^{-1} N application) were reported in the study conducted at Beeville, TX during

1964 and 1965. Endres et al. (2001) reported that N had no significant effect on seed yield of flax in North Dakota. However, crop response to N applications largely depends on moisture availability and initial N content already present in the soil before the additional application of fertilizer. Typically, a crop responds more favorably to N application when initial soil nitrogen levels are low.

1.4.4. Weed control in flax

A major factor limiting the yield of flax is weed management. In general, flax is a poor competitor with weeds (Friesen and Shebeski, 1960; Dew, 1972). Friesen et al. (1990) indicated that the flax was a poor competitor with cereals due to differences in the growth rate. In addition to the poor-competitive nature of flax, availability of herbicides was limited for effective chemical weed control in flax (Morgan et al., 2010). Flax is proned to most of the herbicides available in the market. For example, flax is highly susceptible to sulfonylurea (Hutchison et al., 1984).

1.4.5. Pests and diseases

False Chinch Bugs

False chinch bugs belong to the family Lygaeidae and genus Nysius. The insects are widely distributed in the semi-arid regions of the U.S., including west of the Mississippi River (Karren and Roe, 2001). They also reported that the bugs resume activity in spring after a prolonged overwintering period and move in swarms to the succulent parts of a plant. The insects in large concentrate in clusters near the ground surface. In Utah, most of the infestations were reported in the middle of May to late September at the maturation stage. It was also reported in Texas that the damage was initiated in the late flowering stage and suck the sap from early seed development stage (Morgan, et al., 2010).

Pasmo

Pasmo is a fungal disease caused by *Septoria linicola (Speg.) Garrassini*. The pasmo disease was not problematic in North Dakota (Halley et al., 2004) but has been reported to cause 70% yield reduction in flax in the Manitoba region of Canada (Rashid, 2001).

Other economically important diseases of flax in Texas include damping off or seedling disease (*Rhizoctonia solani, Pythium sp., Fusarium sp*.), rust (*Melampsora lini*), curly top (curly top virus), Aster yellows (*Phytoplasma sp*.), and cotton root rot (*Phymatotrichopsis omnivore*) (Morgan et al., 2010).

1.4.6. Seed and flower colors of flax

Dillman (1946) classified the color of flax seeds as brown, cinnamon brown, yellow, chamois yellow, greenish yellow, mottled (isabella) or mummy brown based upon the color standards (Ridgway, 1912). Tammes (1914) proposed that the presence of a basic G' gene contributes color to the seed. However, a spectrum of seed colors can be possible in the presence of B' and D' factors. Tammes (1915) also indicated that B' and C' were the two major genes contributing to flower color. The presence of both B' and C' resulted in the blue color and absence of either of those factors resulted in white color. Further work of Tammes (1922) revealed that flower color was an interactive effect of six genes (A, D, E, F, B', and C'). Numerous studies (Tammes, 1914 and 1915; Graham and Roy, 1924; Myers, 1936) demonstrated that when a crimped white flower was crossed with a blue flowered plant, a 3:1 F_2 ratio was obtained. Barnes et al. (1960) indicated that the yellow seed color was attributed to the homozygous condition of 1 or more recessive genes. Two of these genes also appeared to be pleiotropic for flower color and one out of two genes were sublethal.

Freeman (1995) reported that brown color seed contained more tannin content in the pigment cells than the yellow color seed. Polyphenols and secondary compounds were included under tannins (Boesewinkel and Bournan, 1984), which impart protection against

pathogens and inhibition of oxidative phosphorylation (Scalbert, 1991). Boesewinkel and Bournan (1984) also reported that the tannins also impart hardiness to seed.

1.4.7. Molecular basis for vernalization and photoperiodism

Studies in *Arabidopsis* (long day plant) revealed the existence of florigen or a part of a floral stimulus called floral integrator, also known as FLOWERING LOCUS T (FT), that elicit the flowering process in plants. The FT gene is expressed in the leaves and protein travels to the meristem where it interacts with another integrator FLOWERING LOCUS D (FD) to initiate the floral stimulus (Turck, et al., 2008; Zeevart, 2008). FT- like genes are ubiquitous and have been found to regulate flowering in most species including wheat (Turck, et al., 2008). Light stabilizes the CONSTANS (CO) protein (circadian regulate gene) and triggers the expression of the FT gene (Corbesier et al., 2007). The photoperiodic induction system in which CO levels are affected by day length and translated in to the regulation of FT (or homologs like VRN3 in cereals) appears to be well conserved among flowering plants (Turck et al., 2008).

The floral integer FT/VRN3 is one of the targets of the vernalization pathway in both *Arabidopsis* and temperate plants (Lee et al., 2000; Chandler et al., 1996). Vernalization seems to alleviate the repression of FT/VRN3 expression. Thus, the control of FT/VRN3 expression may be conserved as an integration point of the photoperiod and vernalization pathway. In *Arabidopsis*, FRIGIDA (FRI) and Flowering Locus C (FLC) genes regulate the vernalization requirement (Koornneef, et al., 1994). SUPPRESSOR OF OVEREXPRESSION OF CO 1(SOC1), AGAMOUS-LIKE 24 (AGL 24), and LEAFY (LFY) are the important regulator genes stimulated by the vernalization in *Arabidopsis* (Melzer, et al., 2008; Liu et al., 2008).

1.5. Objectives

The overall objectives of this research were to: 1) evaluate flax (*Linum usitatissimum* L.), rapeseed (*Brassica napus* L.), safflower (*Carthamus tinctorius* L.) , and camelina (*Camelina*

sativus L.) for their yield and adaptation in different agro-climatic regions of Texas; 2) evaluate the existing genotypes of flax in different adaptive regions of South Texas for their yield and agronomic performance; 3) identify the yield components of flax; and 4) evaluate the effect of photoperiodism and vernalization on the anthesis of different flax genotypes.

CHAPTER II

THE EVALUATION OF COOL-SEASON OILSEED CROPS FOR YIELD AND ADAPTATION IN TEXAS: AN APPROACH FOR SELECTION OF EFFICIENT BIOFUEL FEEDSTOCK

2.1. Introduction

Finding alternate renewable fuels for the replacement of fossil fuels is necessary for global energy sustainability in future. The global petroleum and crude oil consumption has reached about 85 million barrels per day in 2009 and is projected to reach 90 million barrels per day by the end of 2012 (United States Energy Information Administration, 2011). The continuous uptrend of global population will impose an additional demand of 8.5 million barrels per day from 2015 to 2030 (United States Energy Information Administration, 2011). Currently, the United States alone consumes about 19 million barrels of fuel per day (21% of total world consumption) and expected to reach a cumulative consumption of 22 million barrels per day by 2035 (United States Energy Information Administration, 2011). The China expected to consume 17 million barrels per day by the end of 2035 (United States Energy Information Administration, 2011).

Texas is one of the largest biodiesel processing states in the U.S. with a current contribution of 14% (The Energy Report, State Energy Conservation Office, 2007) and has the capacity to expand even further. The current biodiesel and glycerol production capacity of Texas has reached 456 million gallons (United States Energy Information Administration, 2009). However, the availability of soybean and other oilseed crops from Texas is limited, and soybean oil is imported to Texas processing facilities from the mid-western states. To minimize the excessive economic costs resulting from importing feedstock, localized production of feedstock suitable to Texas is necessary. Identifying the most productive local feedstock for biofuel production is a key step in increasing the Texas economy and meeting the future demand for U.S. biofuel production.

The objectives of this research were to evaluate and identify the yield and oil potential and yield limiting factors of numerous cool-season oil-seed crops, including flax, rapeseed or canola, safflower, and camelina for various agro-climatic zones of Texas.

2.1.1. Yield potential of flax

North Dakota is the leading state in flax production with an average yield of 1232 kg ha^{-1} in over 156,000 harvested hectares (USDA-NASS, 2007). Variety yield trials conducted at North Dakota in 2010 reported a flax yield range of 358 kg ha^{-1} to 2744 kg ha^{-1} and an average yield of 1047 kg ha^{-1}. Flax production in Texas started in the early 1900's and peaked in 1949 with 133,198 hectare acreage (USDA-NASS, 2011). In Texas, the most popular varieties from 1960 to 1970 yielded a maximum of 1120 kg ha^{-1} (MP-967 Publication, 1970). However, most of the flax production in Texas at that time was limited to the Southern Blacklands and Coastal Bend region which is non-irrigated production. The national 5-year average yield of flax from 2007 to 2011 was 1186 kg ha^{-1} (USDA-NASS, 2011).

2.1.2. Yield potential of safflower

Results from the Pacific Northwest suggest that spring safflower yield ranged from 720 to 2200 kg ha^{-1}, and oil content ranged from 19 to 37% under dryland conditions in Idaho (Auld et al., 1978). Similar results were reported in Southern Alberta, where spring planted safflower yields ranged from 1120 to 1340 kg ha^{-1} (Mundel, 1981). A variety trial conducted at North Dakota State University revealed that spring safflower yield ranged from 1724 to 2032 kg ha^{-1} with an oil content ranged from 38 to 44% (Berglund et al., 2007). In California, the average yield of spring safflower for 2011 was 1692 kg ha^{-1} (USDA-NASS, 2011). Irrigated safflower yield ranged from 1120 to 4480 kg ha^{-1} in Washington (Nelson, 1964). The national 5-year average yield of safflower in 2011 was 1387 kg ha^{-1} (USDA-NASS, 2011).

2.1.3. Yield potential of rapeseed

Variety trials conducted in North Dakota in 2010 indicated that canola yielded as high as 3920 kg ha^{-1} with average high oil content of 44.8% (Kendel et al., 2010) and an average yield of about 2016 kg ha^{-1}. A national winter rapeseed trial conducted in Southern Great Plains in 2011 reported an average yield of 1892 kg ha^{-1} in Oklahoma, 2470 kg ha^{-1} in Kansas, and 1536 kg ha^{-1} in Texas (SRP 1062 Kansas State Publication, 2012). The national 5-year average yield of canola from 2007 to 2011 was 1539 kg ha^{-1} (USDA-NASS, 2011).

2.1.4. Yield potential of camelina

Agronomic trials conducted at the University of Minnesota for over 30 years resulted in exploration and establishment of camelina in the U.S. as an oilseed crop (Robinson, 1987). Yield of camelina ranged from 600 to 1,700 kg ha^{-1} at Rosemount, MN (Putnam, 1993). However, the yield potential of camelina has remained static over many years since its introduction into the U.S. German plant breeders found transgressive segregation over parental lines in many yield traits for camelina, demonstrating both the high yield potential and capacity for yield improvement in this species (Seehuber et al., 1987). In Montana, it was reported that camelina yielded 330 to 1,700 kg ha^{-1} depending upon the available moisture conditions (MT200701AG revised publication, 2008).

2.1.5. Environmental factors affecting oil content and quality

In the presence of drought conditions, Jensen et al. (1996) found that the oil content decreased from 43.2% to 39.9% in canola. Mailer and Cornish (1987) observed similar results in the oil content of canola (dropped from 36.9% to 31.4%) in the presence of drought. It was also observed that a 1°C rise in temperature at seed development stage resulted in 1.2% (Canvin, 1965) to 1.5% (Ryan, 1979) reduction in oil content in canola.

Fatty acid composition of flax was largely affected by the environmental factors (McNair, 1945). The temperature at 15°C at the boll maturation stage increased the levels of linolenic

acid compared to 30°C (Dybing and Zimmerman, 1966). They also observed that long photoperiods for 20 hours also increased polyunsaturated fatty acids in flax.

Imposing a 90% depletion of available moisture reduced the total oil content of safflower by about 13%, while palmitic and stearic acids contents were reduced by 60 and 70%, respectively (Ashrafi and Razmjoo, 2010). They also reported reduction in linoleic and oleic acid content was about 7 and 11%, respectively.

The previous research in cool-season oil-seed crops explains the general effects of environmental factors on oil content. However, limited information is currently available on cool-season oil-seed crops quality and sunflower is being used to explain the possible effects of specific environmental impact. Harris et al. (1978) indicated that maximum production of oil occurred after an initial lag phase of seed development of sunflower. They also reported that both total oil and linoleic acid reached a maximum just prior to physiological maturity of the seed. A similar pattern was also reported in rapeseed (Fowler and Downey, 1970). Both oleic and linoleic acid were present at all stages of sunflower seed development. Under favorable temperature conditions, linoleic acid was the dominant fatty acid present, ranging from 50% soon after pollination to more than 70% at maturity. The continuous build up of fatty acids throughout seed development indicated that there was no specific stage of development where environmental factors could influence the oil content and quality of sunflower.

Numerous studies in different oilseed crops indicated that the oil content and quality was inversely proportional to the temperature at seed development stage (Harris et al., 1976; Heiser, 1965; Sarmiento et al., 1998). For example, temperature was the main factor affecting sunflower oil characteristics during grain filling stage (Trémolières et al., 1982). The adjustment of planting date to maintain lower temperatures at the flowering and seed maturity stages produced higher quality oil (Anderson, 1977). It was also reported that irrigation could influence the temperature by changing the microclimate of a crop (Pruitt et al., 1983), and result in a decrease of oleic to linoleic acid ratio. Various experiments also

reported that the environmental factors altered the enzymatic activity as well as transportation of organic solutes resulting in the fluctuation of oleate desaturase activity (Steer and Seiler, 1990). It was observed that the ratio of oleic to linoleic acid was increased drastically under water stress conditions in sunflower (Talha and Osman, 1974; Baldini et al., 2000). In contrary, Unger (1982) found very little differences in oil content of sunflower among different water regimes, and Salera and Baldini (1998) found no effect of water management on fatty acid composition.

Path-coefficient analyses indicated that minimum temperature and total solar radiation had the greatest direct effect on seed oil concentration in wild annual sunflower, though the influence was very low (Seiler, 1986). In the cultivated hybrid, minimum temperature and day length had the highest direct effect on seed oil concentration. Seiler (1986) also indicated that minimum temperature and solar radiation had the primary influence on oleic acid concentration in the wild and cultivated sunflower, with maximum temperature being less important. Linoleic acid concentration was primarily influenced (negatively) by minimum temperature and solar radiation as indicated by path-coefficient analyses in wild and cultivated sunflower.

Assuming similar results of sunflower are valid to cool-season crops, under North Texas conditions, where the temperatures are normally high during the late-spring season, manipulation of microclimate by irrigation and decreasing the canopy temperatures would benefit the oil quantity and quality in oilseed crops. The main objectives of the study were to identify the adaptation of flax (*Linum usitatissimum* L.), rapeseed (*Brassica napus* L.), safflower (*Carthamus tinctorius* L.), and camelina (*Camelina sativus* L.) to various cropping environments in Texas, ranging from a humid subtropic (Weslaco) environment to the semi-arid temperate (Amarillo/Etter) environment. Secondly, identify the highest yielding species and/or genotypes of cool-season oilseed crops for oil production within the different production regions and crop management areas of Texas.

2.2. Materials and methods

Fifty-one genotypes of four winter and spring-type oilseed crops (flax, rapeseed, safflower, and camelina) were evaluated at nine Texas AgriLife Research and Extension Centers across the Texas (Table 2.1, Table 2.2 and Fig. 1.1). Genotypes were selected based on performance data from various oilseed evaluation trials across the U.S., agronomic traits, and seed availability. The weather details for each individual location during tested years are compiled in Table 2.3. The experiments were configured in a randomized complete block design with three replications at each of the nine locations. The experiments were conducted for three growing seasons. The planting dates were site-specific with temperature and potential winter-kill representing the primary factor. In the south and southeast locations (College Station, Beaumont, Beeville, Uvalde, and Weslaco), both the spring and winter-type genotypes were planted in the fall (October-December). In North Texas locations, Prosper, Vernon, Amarillo, and Lubbock, winter-types were planted in fall, while spring-types were planted in late-winter or early spring. The seeding rates were 39, 5.6, 30, and 5.6 kg ha^{-1} for flax, rapeseed, safflower, and camelina respectively. Fertilizer recommendations and other management practices varied by location, but were based on best management strategies known for these crops.

2.2.1. Important management practices and production constraints

Weslaco

In Weslaco, the trials were non-irrigated and were planted on October 23, November 18, and November 4 for each production seasons in 2007, 2008, and 2009, respectively. The management practices followed the best management practices known for each of these species in the Rio Grande Valley. Weeds, diseases, and insects were adequately managed to prevent minimal yield loss during all growing seasons. However, powdery mildew and lodging were a problem in the late-maturing genotypes. All treatments were hand-harvested on April 1, April 15, and May 7 for three production seasons, respectively.

Beeville

In Beeville, two out of three years were severely drought affected and produced low yields. In the 2009-2010 production year, no yields were obtained due to poor stands. All species and genotypes were planted on November 5 and most of the crops were harvested by mid-May. Insects and pathogens were not problematic in this location; however, poor crop stands resulted in high weed pressure in the growing season.

Uvalde

In Uvalde, the data were not obtained in first two years due to severe drought and stand establishment problems. In the third year, some stand was established due to some rainfall in November and December months.

Beaumont

The planting of the cool-season annual oilseed trials at Beaumont in 2008-2009 was delayed until December due to excessive soil moisture of the clay soils in the Beaumont area. The study was planted on February 25 and emergence of all species was completed within 10 days. Frequent rains prevented most cultural practices during crop development. Grassy weeds were the biggest problem in cropping season. Due to unfavorable rainfall conditions and subsequent weed problems, no data was obtained in all three years, with the exception of flax in 2009.

College Station

Management practices were similar in the College Station for all years, unless specified otherwise. In College Station, all species were planted on November 10, 2007 for the 2007-2008 cropping season. Two planting dates were established in the cropping season 2008-2009. Winter rapeseed and winter camelina were planted on October 24, 2008 and the spring rapeseed, camelina, flax, safflower, and radish were planted November 17, 2008. Before planting, the soil was cultivated with a tandom disc followed by a culti-packer.

Treflan® was applied and incorporated on field prior to final tillage to assist in controlling winter weeds. Ignite 280® and Roundup were sprayed on the experimental area just prior to planting to eliminate the emerged weeds. The spray nozzles were Teejet 80-02 DG tips with 125 kPa pressure, to spray 140 liters ha^{-1}. All plots were planted with Hege-500 small plot planter with 7 rows and 20 cm row spacing. Rainfall was below average for the fall of 2008 and 0.64 cm of irrigation was applied, a week after each planting. The experiment was fertilized with 57 kg ha^{-1} of N (Ammonium sulfate (21-0-0-24) on December 17, 2008. The fertilizer was sprayed at 140 liters per hectare using the 110-03 TeeJet tips on a 9 m Remcor Boom sprayer. Several applications of Dimethoate® (insecticide) were applied at the rate of 250 ml per acre to control aphids (*Lipaphis erysimi*) based on estimated thresholds. Powdery mildew (*Blumeria graminis*) was observed on both the winter and spring rapeseed and camelina genotypes and a fungicide (Propiconazole (41.8%)) was applied to these genotypes to preserve the yield potential.

In 2009-2010, at College Station, all winter genotypes (except safflower) were planted on October 20, 2009. All spring genotypes and safflower were planted on November 13, 2009. Plots were fertilized with a broadcast application of 78 kg ha^{-1} N (Ammonium sulfate 21-0-0-24) on December 11, 2009. Moisture was sufficient throughout the fall, and irrigation was not needed for stand establishment. All experiments were topdressed with 32-0-0 at the rate of 78 kg ha^{-1} N.

Prosper

Due to the high clay content soils at the Prosper location, narrow tillage and planting window exist. The conditions were favorable only in 2007-2008. During production year 2008-2009, trials were seeded in September into dry soil, and crop emergence did not occur until late November following the first precipitation event after planting. The late emergence predisposed the small plants to winterkill during the first freeze (below -8°C) in early December. Due to prolonged saturated soils in September through early October of 2009, winter genotypes were planted in mid-October, and an acceptable stand was not

achieved. Likewise, a wet spring delayed planting of the spring genotypes until in mid-April. Adequate stands were obtained with the spring genotypes, but an extended late spring drought prevented development of many reproductive structures or yield potential.

Vernon

In Vernon, the location was a non-irrigated location and stand establishment was problematic in each of the three years of the experiment. Spring planted crops failed to produce measurable seed yields due to the rapid onset of high temperatures and dry condition in all three production years. Delaying planting until adequate soil moisture was present resulted in cold soil temperatures poor stand establishment and winter in the stand establishment stage and high temperatures in the mature stage were detrimental to growth and development.

Lubbock/Pecos

In Lubbock, during the 2007-2008 cropping season, all cool-season crops were planted in the third week of September and harvested by the end of July. The winter of 2007-2008 was extremely dry and windy; these environmental conditions caused reduced yields in many of the cool- season oil seed crops. During 2008-2009, the winter mustard/HEAR lines seeded in Bailey Co. on Sept. 19 failed to establish due to dry conditions.

At Pecos, where saline irrigation and soil conditions prevail, two winter hardy safflower lines and two camelina lines were seeded on October 23, 2009. The damage from army worms and subsequent Botrytis head rot reduced the safflower yields to near zero, and the plots were not harvested.

Etter

In the 2008-09 season, twelve genotypes of rapeseed and eight genotypes of winter safflower for the 2008-09 crop year were planted in Etter on September 16th at a depth of approximately 1.27 cm. with the aid of depth bands attached to a Hege small plot grain drill.

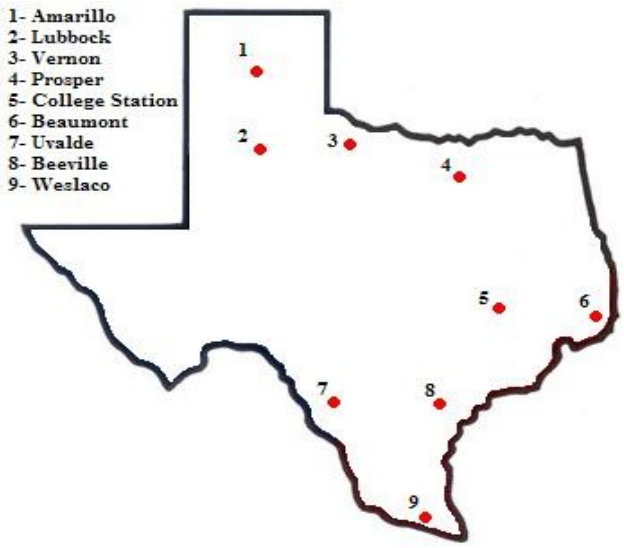

Fig. 2.1. Cool-season oilseed testing locations in Texas during 2007-2010.

Table 2.1. Evaluated cool-season oilseed species/genotypes in Texas during 2007-2010.

Species	Variety	Released by	Species	Variety	Released by
LEAR[a]	ARC 97003	UoA[c]	**Flax**	AC Carnduff	AAFC[g]
	ARC 98017	UoA		AC Emerson	AAFC
	Ericka	IAES[d]		AC Linora	AAFC
	Jetton	Unknown		AC McDuff	AAFC
	Sumner	KSU		AC Lightning	AAFC
	Wichita	UoI[e]		Carter	NDSURF[h]
	Bridger	Unknown		MacBeth	AAFC
	DKW 13-86	Monsanto		Omega	NDSURF
	DKW 13-69	Monsanto		Nekoma	NDSURF
	Sunrise	IAES		Pembina	NDSURF
	Sterling	IAES		Prairie Thunder	AAFC
	Gem	UoI		Prairie Grande	AAFC
HEAR[b]	White Bionute	UoI		Rehab-94	Unknown
	White Idagold	UoI		York	NDSU
	White pacific Gold	UoI		Prairie Blue	AAFC
Camelina	BSX – WG2	Blue Sun	**Safflower**	PI-406002	TTU[i] (Exp.)
	BSX-WG3	Blue Sun		PI-544006	TTU (Exp.)
	BSX-WG4	Blue Sun		PI-544017	TTU (Exp.)
	BSX-WG5	Blue Sun		PI-388901	TTU (Exp.)
	Baltensperger	SDSU[f] (Exp.)		PI-405985	TTU (Exp.)
	BSX-WG21	Blue Sun	**Radish**	CSA-112	Unknown
	BSX-WG72	Blue Sun		CSA-115	Unknown
	Cheyenne	Unknown			
	Calena	Unknown			
	Celine	Unknown			

[a]LEAR- Low Euricic Acid Rapeseed
[b]HEAR- High Euricic Acid Rapeseed
[c]UoA- University of Arkansas
[d]IAES- Idaho Agricultural Experiment Station
[e]UoI- University of Idaho
[f]SDSU- South Dakota State University
[g]AAFC- Agriculture and Agri-Food Canada[h]NDSURF- North Dakota State University Research Foundation
[i]TTU- Texas Tech University

Table 2.2. Experimental locations (South to North) and soil information for cool-season oil-seed crops in Texas during 2007-2010.

Location	Average Elevation above sea level (m)	Latitude (North)	Longitude (West)	Soil classification[a]
Weslaco	24	26°9′	97°59′	Sandy loam soil
Beeville	64	28°24′	97°45′	Parrita sandy loam
Uvalde	277	29°12′	99°47′	Uvalde silty clay loam
Beaumont	5	30°04′	94°07′	Silty loam
College Station	112	30°36′	96°18′	Ships clay
Prosper	208	33°14′	96°47′	Houston clay
Vernon	361	34°09′	99°17′	Silty clay loam
Lubbock	992	33°33′	101°53′	Acuff silty clay loam
Etter	1099	35°11′	101°50′	Sherm silty clay loam

[a]Soil Survey Staff, NRCS, USDA, 2011

Table 2.3. Average monthly precipitation and minimum and maximum monthly average temperature distribution at experimental locations (South to North) in Texas during 2007-2010.

Location	Item	Month											
		J	F	M	A	M	J	J	A	S	O	N	D
Weslaco	T_{max}[a]. (˚C)	21	24	27	30	33	36	35	36	32	30	27	23
	T_{min}[b]. (˚C)	9	12	14	18	22	25	25	25	17	16	14	10
	RF[c] (cm)	5	3	1	2	6	4	22	6	6	2	1	3
Beeville	$T_{max.}$ (˚C)	18	22	25	27	31	33	33	35	32	30	25	20
	$T_{min.}$ (˚C)	6	9	12	16	20	22	22	23	20	16	11	7
	RF (cm)	7	3	4	5	4	6	19	6	14	1	1	2
Uvalde	$T_{max.}$ (˚C)	14	17	23	25	28	31	31	34	31	26	14	17
	$T_{min.}$ (˚C)	0	1	7	11	17	21	22	22	18	8	0	0
	RF (cm)	8	4	12	8	7	10	14	8	8	1	8	5
Beaumont	$T_{max.}$ (˚C)	16	18	22	26	30	31	33	33	31	28	22	18
	$T_{min.}$ (˚C)	5	7	10	15	20	22	24	24	21	15	11	7
	RF (cm)	13	8	10	10	13	18	25	15	21	5	9	10
C. Station	$T_{max.}$(˚C)	15	18	22	26	30	34	34	36	32	28	23	16
	T_{min}(˚C)	2	4	8	12	18	22	23	23	19	12	8	3
	RF (cm)	10	3	8	7	9	7	13	7	11	10	7	6
Prosper	$T_{max.}$ (˚C)	13	15	22	25	29	34	35	37	32	26	21	15
	$T_{min.}$ (˚C)	0	2	7	11	17	22	23	23	19	11	8	1
	RF (cm)	8	6	14	11	17	12	10	7	12	17	9	6
Vernon	$T_{max.}$ (˚C)	12	14	21	24	28	34	35	37	31	26	21	12
	$T_{min.}$ (˚C)	-2	0	6	10	15	21	22	23	18	11	6	-1
	RF (cm)	3	3	4	7	9	13	6	4	9	5	1	2
Lubbock	$T_{max.}$ (˚C)	11	15	20	23	27	33	31	33	29	24	19	2
	$T_{min.}$ (˚C)	-4	-2	2	6	12	18	19	18	14	8	1	-3
	RF (cm)	2	2	5	3	8	8	9	5	5	3	0	1
Etter	$T_{max.}$ (˚C)	10	12	19	22	26	33	32	32	29	23	18	11
	$T_{min.}$ (˚C)	-7	-5	1	4	10	17	18	18	13	6	0	-5
	RF (cm)	1	1	4	5	5	10	5	10	8	4	2	1

[a]Tmax- Maximum monthly average temperature
[b]Tmin- Minimum monthly average temperature
[c] RF- Monthly average precipitation

The plot area was pretreated with trifluralin to aid in weed control. Fertilizer was applied at 67 kg of nitrogen and 35 kg of phosphorus per hectare prior to planting. A disk plow and culti-packer was used to prepare the ground for planting. All varieties were watered with a linear irrigation system to enhance seed germination and seedling establishment. Spring oilseed crops and varieties of rapeseed, camelina, and flaxseed were planted on March 28th. All varieties emerged but the rapeseed plots were destroyed by rabbits. Camelina and flaxseed varieties were harvested in late July.

2.2.2. Data analysis

The data were analyzed by using SAS (SAS Institute, 2008) software using Proc GLM procedure. The mean yield for each crop species for a particular year was obtained by combining all the genotypes. Due to the complexity of trials at different locations and the difference in planting seasons (fall versus spring), genotypes among the locations and the location across years, the data were combined for each location across the years. Duncan multiple range tests were performed at 0.05 significance level to determine the differences among tested crop species across the locations.

2.3. Results and discussion

2.3.1. Yield potential of evaluated crop species in Texas

Weslaco

In Weslaco, spring rapeseed yielded highest with an overall mean of 1381 kg ha^{-1}, followed by safflower with a mean yield of 1280 kg ha^{-1} (Table 2.4, 2.5). Camelina yielded lowest with a three year average of 160 kg ha^{-1}. The environmental factors were mostly favorable in the third year (2009-2010) compared to the first two years. Spring rapeseed had consistently higher yields compared to other cool-season crops throughout all three tested years. Spring rapeseed, safflower and flax seemed to be well adapted in this region. Camelina yield was consistently lower and did not appear to be adapted to this region.

Based on visual observations, yield limiting factors for flax included excessive vegetative growth, an indeterminate fruiting habit, and the tendency for mature pods to dehisce.

Beeville

In Beeville, spring rapeseed yielded highest with an overall mean of 2378 kg ha^{-1}, followed by flax with a mean yield of 1585 kg ha^{-1}. Camelina yielded lowest with a two- year average of 972 kg ha^{-1}. During 2007-2008, winter mustard produced 560 kg ha^{-1}. Safflower yields ranged from 524 kg ha^{-1} (PI 405985) to 1644 kg ha^{-1} (PI 544006) with an average yield of 1058 kg ha^{-1}. Flax yields ranged from 261 kg ha^{-1} (AC Lightning) to 934 kg ha^{-1} (MacBeth). In 2008-2009, the conditions were more favorable to plant growth and development. Camelina failed to produce measurable quantity of seed because of the poor competition with weeds and very limited herbicide weed management. In 2008-2009, spring rapeseed mean yield was 3924 kg ha^{-1}, while safflower and flax mean yield was 1579 kg ha^{-1} and 2611 kg ha^{-1}, respectively (Table 2.4). The crops were not harvested in 2010 due to poor stands.

Uvalde

In Uvalde, spring rapeseed yielded highest with an overall mean of 1010 kg ha^{-1}, followed by flax with a mean yield of 941 kg ha^{-1}. Winter mustard yielded lowest with one year genotype average of 149 kg ha^{-1}. The data was obtained only in 2009-2010.

Beaumont

In Beaumont, flax was the only crop that was harvested in 2009 with a mean yield of 1072 kg ha^{-1}. Beaumont failed to produce any yields in all cool-season crops except flax in all three tested years due to untimely rainfall and subsequent weed problems.

College Station

In College Station, flax yielded the highest with an overall mean of 1958 kg ha^{-1}, followed by safflower with a mean yield of 1400 kg ha^{-1}. Camelina yielded lowest with a three-year average of 612 kg ha^{-1}. Seed yield of winter rapeseed ranged from 1,531 kg ha^{-1} (White Pacific Gold) to 210 kg ha^{-1} (White Bionute) with a mean of 847 kg ha^{-1} for the cropping season 2007-2008. Spring rapeseed yielded in the range of 959 kg ha^{-1} (Gem) to 279 kg ha^{-1} (Sterling) with the mean yield of 727 kg ha^{-1}. However, there was no difference in yield when averaged across all genotypes between the spring and winter rapeseed. The seed yield of camelina ranged from 536 kg ha^{-1} (BSX-WG1) to 118 kg ha^{-1} (Cheyenne) with an average yield of 406 kg ha^{-1}.

In College Station, during 2008-2009, spring rapeseed yielded highest with an average seed yield of 2007 kg ha^{-1}, followed by flax with an average of 1671 kg ha^{-1}. Winter rapeseed yield ranged from 1154 kg ha^{-1} (Rally) to 2117 kg ha^{-1} (Rossini) with a mean yield of 1645 kg ha^{-1}. Safflower and winter rapeseed yielded comparatively high. Safflower yield ranged from 1490 kg ha^{-1} (PI-406002) to 926 kg ha^{-1} (PI-405988) with a mean yield of 1477 kg ha^{-1}. During the 2009-2010 cropping season, flax yielded higher compared to other cool-season crops with an average yield of 2092 kg ha^{-1}, followed by winter rapeseed with an average yield of 1604 kg ha^{-1}.

Prosper

In Prosper, Two out of three years (2008-2009 and 2009-2010), cool-season crops failed to produce significant amounts of seed yield. Safflower yielded highest with an overall mean of 2100 kg ha^{-1}, followed by flax with a mean yield of 942 kg ha^{-1}. However, mean data represented only one year data during 2007-2008. During 2007-2008, safflower yielded highest with a mean seed yield of 2100 kg ha^{-1} and a maximum yield of 2218 kg ha^{-1} (PI 544006). Spring flax and winter rapeseed means were 942 kg ha^{-1} and 842 kg ha^{-1}, respectively. Camelina and spring rapeseed yields were poor in Prosper during 2007-2008.

For winter rapeseed, the cultivars White Bionute and White Idagold failed to produce harvestable seed.

Lubbock

In Lubbock, spring rapeseed yielded highest with an overall mean of 1253 kg ha^{-1}, followed by safflower with a mean yield of 1078 kg ha^{-1}. Fall sowed winter rapeseed and spring sowed flax and flax produced no yield at this location. In 2008, the spring rapeseed produced 480 kg ha^{-1}. In 2009, safflower yielded highest with 1158 kg ha^{-1}, followed by spring rapeseed with 1104 kg ha^{-1}. In 2010, the safflower produced 996 kg ha^{-1}, while all other crops failed to produce any yields in 2010.

Etter

In Etter, safflower yielded highest with an overall mean of 1210 kg ha^{-1}, followed by winter mustard with a mean yield of 565 kg ha^{-1}. Camelina yielded lowest with a three year average of 322 kg ha^{-1}. In Etter, all winter crops of 2007 and spring crops of 2008 were largely affected by damage caused by rabbits. In the spring of 2008, poor stands contributed to the decreased yields of all cool-season crops. Spring and winter rapeseed failed to produce any yields in 2009-2010 due to severe winter injury. Safflower produced higher yields compared to other cool-season crops in both 2008-2009 and 2009-2010 with a mean yield of 1045 and 1375 kg ha^{-1}, respectively.

2.3.2. Yields of evaluated crop species

Rapeseed

Generally, spring rapeseed seemed to be well adapted to most of the sub-tropical climates (College Station, Weslaco, and Beeville) of Texas with the state average of 1372 kg ha^{-1} (Table 2.5). Spring rapeseed recorded the highest yield (2378 kg ha^{-1}) in Beeville. College Station and Weslaco locations produced reasonable yields of spring rapeseed averaged

Table 2.4. Mean yields of flax, rapeseed, safflower, and camelina in individual years for all tested locations in Texas during 2007-2010.

	Weslaco				Beeville				Uvalde			
	2008	**2009**	**2010**	**Mean**	**2008**	**2009**	**2010**	**Mean**	**2008**	**2009**	**2010**	**Mean**
WR[a]	.	510 a	555 ab	533	560 a.	2302 ab	.	1432	.	.	149 b	.
SR[b]	1676 a	982 a	1484 a	1381	832 a	3924 a	.	2378	.	.	1010 a	.
Flax	1670 a	369 a	949 ab	977	560 a	2611 ab	.	1585	.	.	676 ab	.
Camelina	135 b	.	183 b	160	589 a	1354 b	.	972	.	.	415 ab	.
Safflower	1352 a	1595 a	892 ab	1280	1058 a	1579 b	.	1369	.	.	941 a	.
	Beaumont				**College Station**				**Prosper**			
	2008	**2009**	**2010**	**Mean**	**2008**	**2009**	**2010**	**Mean**	**2008**	**2009**	**2010**	**Mean**
WR	.	.	.	.	847 ab	1645 a	1604 ab	1322	842 ab.	.	.	.
SR	.	.	.	.	727 ab	2007 a	1232 ab	1366	324 b	.	.	.
Flax	.	1072	.	.	2109 a	1671 a	2092 a	1958	942 ab.	.	.	.
Camelina	.	.	.	.	406 b	906 a	523 b	612	.	.	.	.
Safflower	.	.	.	.	1369 a	1477 a	1353 ab	1400	2100 a.	.	.	.
	Vernon				**Lubbock**				**Etter**			
	2008	**2009**	**2010**	**Mean**	**2008**	**2009**	**2010**	**Mean**	**2008**	**2009**	**2010**	**Mean**
WR	.	.	.	.	.	.	.	.	565 a	.	.	.
SR	.	.	.	.	480 a	1104 a	.	1253	.	.	.	.
Flax	.	.	.	.	.	.	.	.	234 a	450 b	.	322
Camelina	.	.	.	.	420 a	240 b	.	354	321 a	.	.	.
Safflower	.	.	584	.	.	1158 a	996 a	1078	1045 a	1375 a	.	1210

[a]WR= Winter Rapeseed

[b]SR= Spring Rapeseed

Note: Yields were compared among different species within a year and within a location.

across three site-years due to good emergence and favorable environmental conditions like precipitation and less insect and disease pressure. The spring rapeseed yield potential appeared to be limited in Amarillo and Vernon because of the late-spring heat conditions that prevailed during the reproductive stages of the plant development. Spring planted cool-season crops did not have sufficient time to develop adequate biomass prior to the on-set of high temperatures. Additionally, flowering occured during high heat stress, which may negatively impact pollination and seed development. However, the spring rapeseed yielded well in Lubbock/Pecos (1253 kg ha^{-1}). The emergence and stand establishment of all winter type cool-season crops were largely affected by frost injury in most of the north locations (Amarillo, Lubbock, Vernon, and Prosper) where susceptible growth stages (<4 leaf) coincided with the freezing temperatures. For most of the spring season-cool crops, the planting dates were delayed until March in the north to avoid the damage due to the freezing injury. Winter rapeseed yielded highest in Beeville and College Station because of the mild temperatures and minimal winter-kill. However, the spring rapeseed yielded comparatively higher than the winter rapeseed in almost of the tested locations due to less abiotic stress due to cold injury.

Flax

Flax had wide range of adaptability in diverse environments of Texas, except in northern locations like Amarillo, Lubbock, and Vernon, which was supported by Mediterranean and Southwest Asian origin (Millam et al., 2005). Flax yield ranged from 1671 to 2109 kg ha^{-1} with a three-year average of 1958 kg ha^{-1} in College Station, where the yield-limiting stresses like cold injury, heat stress, and pests and diseases were minimal. Flax yielded more than 2000 kg ha^{-1} in two out of three years in College Station. Beeville produced the second highest yield for flax with a two-year average of 1585 kg ha^{-1}, where the drought conditions were predominant. Flax yielded relatively high in South Texas locations and supported the fact that flax acreage was mostly concentrated on the Coastal Bend of Texas in 1900's due to high level of adaptation. Flax yielded poor in most of the North Texas locations due to adverse cold and heat temperatures during crop growth and development stages.

Camelina

Camelina produced less than 500 kg ha^{-1} in most of the locations, except in College Station and Beeville. The major problem encountered and that contributed to lower yields of camelina was poor stand establishment due to small seed size.

Safflower

Safflower produced decent yields in diverse environments of Texas (state yield average of 1240 kg ha^{-1}) because of its relative tolerance to drought conditions as supported by Kephart, et al. (1990). Safflower produced higher yield in College Station with a yield range of 1353 to 1477 kg ha^{-1} and three-year mean yield of 1400 kg ha^{-1} due to minimal yield-limiting factors such as pests, and diseases. In Weslaco, safflower yield ranged from 892 to 1352 kg ha^{-1} with a three-year average of 1280 kg ha^{-1}. In Beeville, safflower yield ranged from 1058 to 1579 kg ha^{-1} with a two-year average of 1369 kg ha^{-1}. In Etter, safflower yield ranged from 1045 to 1375 kg ha^{-1} with a two-year average of 1210 kg ha^{-1}. Safflower yielded more than 1200 kg ha^{-1} in 4 out of 9 locations.

2.3.2. Oil content

Due to missing data in most of the locations and lack of measurable seed for analyzing the oil content, the data was combined across years and all locations to obtain the mean oil content for each individual crop species. The oil content (w/w) was highest in flax (38.3%) followed by winter rapeseed (36.2%). However, there was no difference between the oil contents of flax and winter rapeseed ($p<0.05$). The large error variance produced in combining the locations might have masked the real difference between the oil content of the different species. If the total oil content was estimated on a land area basis, based on the average state yields of Texas, spring rapeseed yielded about 477 L ha^{-1}, flax yielded 412 L ha^{-1} , and safflower yielded about 271 L ha^{-1}. If the maximum yield potential for each species in Texas was considered, spring rapeseed yielded about 832 L ha^{-1} and flax yielded

Table 2.5. Mean yield of flax, rapeseed, safflower, and camelina by location in Texas during 2007-2010.

Location/species	Spring Rapeseed	Winter Rapeseed	Flax	Camelina	Safflower
Weslaco [c]	1381a	533 ab	977 ab	160 b	1280 a
Beeville [b]	2378 a	1432 a	1585 a	972 a	1319 a
Uvalde [a]	1010	149	676	415	941
Beaumont [a]	.	.	1072	.	.
College station [c]	1366 a	1322 a	1958 a	612 b	1400 a
Prosper [a]	842	324	942	.	2100
Vernon [a]	.	.	.	.	594
Lubbock [d]	1253 a	.	.	354 a	1078 a
Etter [d]	.	565	322	322	1210
State Average	1372	720	1075	473	1240

[a] represents one year of data
[b] represents two years of data
[c] represents three years of data
[d] represents mixed years data
. = no data;
Note: The means were assigned for a particular location if there were at least two years' of data; if there is only one year data, mean yield of genotypes were reported.

Table 2.6. Mean oil content of flax, rapeseed, safflower, and camelina evaluated in Texas during 2007-2010.

Crop	Oil %(w/w)[a]
Flax	38.3 a
Winter Rapeseed	36.2 a
Spring Rapeseed	34.5 ab
Camelina	28.2 b
Safflower	21.4 c

[a] Mean oil content of each species was calculated by combining two years data

758 L ha^{-1}. Even though safflower produced decent oil-seed yields in most of the locations, the lower oil content of safflower (Table 2.6) limits the biofuel potential of safflower.

2.4. Conclusions

The results suggested that flax had a wide range of adaptability in Southeast Texas and had high oil content (38.2%). The state average yield of flax was 1072 kg ha^{-1} with the highest yield in College Station (1958 kg ha^{-1}). This level of yield potential is comparable to the state average yield of North Dakota (1232 kg ha^{-1}) (USDA-NASS, 2011). However, lower temperatures during stand establishment stage and high temperature stress at critical reproductive stages in the Northern locations of Texas lowered the state flax yields significantly. Flax trials conducted along the Coastal Bend of Texas in 1960-1970 reported a maximum yield of 1120 kg ha^{-1}(MP-967 publication, 1970), which was much lower than the maximum yield of current trials (1958 kg ha^{-1}). Yield improvement of flax from 1930 to now has been nearly double, mainly due to improved varieties and agronomic practices.

Rapeseed also had potential as a biofuel crop within specific regions of Texas, Spring rapeseed yielded highest in Beeville with a two-year mean yield of 2378 kg ha^{-1}, compared to the state average yield was 1372 kg ha^{-1}. The average yield of rapeseed in Texas was lower than North Dakota (2016 kg ha^{-1}) in 2010 (USDA-NASS, 2010). The yield results from national canola trial (SRP 1062 Kansas State Publication, 2012) suggested the mean rapeseed yielded 1892 and 2470 kg ha^{-1} in Oklahoma and Kansas, respectively. These yields were comparable to the mean yield of Beeville in Texas. However, it is also important to take environmental and soil conditions and management practices in to consideration before comparing the yields of different agri-climatic zones.

Safflower had a broad range of adaptability to the diverse environments of Texas as it produced relatively high yield in most of the regions of Texas. Safflower average yield of Texas in three tested years was 1240 kg ha^{-1}. However, the state average yield of safflower in Texas was about 250 kg ha^{-1} lower than the national safflower average (USDA-NASS, 2011). Additionally, lower oil content will limit its biofuel potential in Texas and the nation.

The careful selection of safflower improved varieties in North Dakota State University suggested the maximum oil content of 44% is possible (Berglund et al., 2007). Cultivars with higher oil content coupled with selection for improved, yield potential could make safflower a possible cool-season oilseed crop for Texas.

The yield potential of camelina in Texas was generally lower than the yields of other camelina producing states like Minnesota (Putnam, 1993) and Montana ((MT200701AG revised publication, 2008). However, the main problem encountered in the camelina production in a majority of Texas locations was poor stand establishment due to small seed size.

Based on the results, spring rapeseed and safflower were the two prominent crop species for diverse environments of Texas. Flax was well adapted to southeast Texas, and spring rapeseed and flax have potential for biofuel feedstock production in Texas. With enhanced oil content, safflower could be a potential biofuel feedstock in Texas.

CHAPTER III

EVALUATION OF FLAX GENOTYPES IN SOUTHEAST TEXAS

3.1. Introduction

Flax (*Linum usitatissimum* L.) is an oilseed and fiber crop (Jhala and Hall, 2010), and belongs to the family Linaceae. Flax is believed to have originated in Mediterranean regions and/or Southwest Asia (Millam et al., 2005). Currently, flax is grown on 2.2 million ha in diverse environments around the world (Food and Agricultural Organization, 2010). Current flax production is mostly concentrated in Canada, China, India, Russia, Kazakhstan, and Ethiopia (Food and Agricultural Organization, 2010). Flax has many industrial and health benefits. Apart from variety of essential omega-3-fatty acids (linolenic acid, oleic acid, and linoleic acid), flax is also rich in proteins (26.9 - 31.6%), lipids (31.9 - 37.8%, dry weight basis), and dietary fiber (36.7 - 46.8%) (Hettiarachchy et al., 1990). Flax is proven to contain anti-carcinogenic properties (Lay et al., 1989) and many anti-disease compounds (Stitt, 1990). In addition to the various health benefits, flax also can be used in manufacturing of paper, plastic, and numerous derived industrial products (Domier et al., 2000).

3.1.2. Yield potential of flax in the United States

North Dakota is the leading state for flax production (Census of Agriculture, NASS 2007). The state average yield was approximately 1320 kg ha^{-1} for the total harvested acreage of 157,895 ha in 2011. Variety yield trials conducted at North Dakota in 2010 reported a flax yield range of 358 kg ha^{-1} to 2744 kg ha^{-1} and an average yield of 1047 kg ha^{-1}. In Texas, recommended varieties yielded a maximum of 1120 kg ha^{-1} in 1960-1970 (Hodges et al., 1970). During this period, most of the flax production in Texas was limited to the coastal bend under non-irrigated conditions.

3.1.3. Flax history in Texas

Flax production was first recorded in South Texas started in 1938 with 405 ha. and peaked in 1949 with approximately 133,198 ha. (Census of Agriculture, NASS, 2007). Flax was grown in Texas as a crop which was planted in the fall with the small acreage concentrated in the coastal area, primarily north of Corpus Christi (Atkins et al., 1962). Attempts were made to extend the acreage to North Texas and the Panhandle of Texas, but these attempts were unsuccessful. In 1950, the severe drought caused a significant decline in flax commercial seed production (Morgan et al., 2010). In 1961, flax production declined even further to 56,680 ha. Since 1980, flax production in Texas has remained negligible (USDA-NASS, 2011)

3.1.4. Cold tolerance in flax

Rhavitin (1935) reported that seedlings in the 6-leaf stage survived at -1.7^{o}C after hardening for three days at 0 - 4.4°C. Harrington (1936) found that the cold injury in flax was minimal after the 2-leaf growth stage. Ivanov (1933) indicated that the effects of prolonged cold temperatures were largely reflected in retarded growth and late flowering. He also reported that cold temperature resulted in elongation of stems and an increase in total dry weight. A study conducted by Davis (1923) on fiber flax concluded that there was a direct relationship between cold tolerance and flax wilt (*Fusarium lini*). But subsequent studies suggested that there was no correlation between cold tolerance and wilt (Kugler and Remussi, 1939).

Flax is usually grown in Texas as a fall season crop (planted in mid October to late November), during which plants are exposed to freezing temperatures at various stages of early plant growth. In Texas, winterkill was reported in 7 out of 27 years starting in 1940 (Omran et al., 1968). There were attempts of identifying the best genotypes for cold tolerance in the 1930's to 1960's, and due to the disappearance of flax after 1980, little research emphasis has focused on this topic (NASS, 2007). Thus, identifying flax genotypes with suitable cold tolerance is one of the most critical aspects of flax production in Texas.

3.1.5 Genotype evaluation and selection

Identifying appropriate genotypes for a particular climatic region is essential for crop development and improvement. This task can often be established by conducting preliminary yield and agronomic experiments, especially if the species is new to a particular environment. Preliminary yield experiments with limited genotype selection creates an opportunity to identify potential parental sources for future breeding programs but also to standardize the agronomic practices necessary to maximize yield. Extending the evaluation to multiple locations following the preliminary yield testing develops an understanding of genotype-environment interactions and site-specific adaption. The adaptation and performance of the different genotypes depends upon the selection of genotypes for a specific trait of interest and environmental conditions for which it is developed. The effective partitioning of environmental interactions among different genotypes also creates an opportunity for a breeder to accurately classify them under different adaptive regions. For example, the accurate classification of winter and spring grown flax based on their environmental adaptation would set certain agronomic management practices (planting date, optimum application of fertilizers, prediction of biotic and abiotic stresses) to follow for that particular region to maximize production. Thus, the main objective of the study was to evaluate existing flax genotypes for yield and agronomic performance in different adaptive regions of South Texas.

3.2. Materials and methods

Twenty genotypes of flax were evaluated at three different locations in South Texas (College Station, McGregor, and Yoakum) for three consecutive years between 2008 and 2011 (Table 3.1). The soil and climate information for the three tested locations is summarized in Tables 3.2 and 3.3. The soil classification in the College Station, McGregor, and Yoakum locations are Ships clay, San Saba clay, and Tremona loamy fine sand, respectively (Soil Survey- USDA, 2011).

Table 3.1. Flax genotypes evaluation for yield, adaptation and quality at College Station, McGregor, and Yoakum, Texas during 2008-2011.

Genotype	Developer	Release Date
AC Carnduff	AAFC[a]	1996
AC Emerson	AAFC	1994
AC Lightning	AAFC	2001
AC Linora	AAFC	1991
AC McDuff	AAFC	1993
AC Watson	AAFC	1995
Prairie Thunder	AAFC	2006
Prairie Blue	AAFC	2006
Carter	NDSURF[b]	2004
Nekoma	NDSURF	2002
Pembina	NDSURF	1999
York	NDSURF	2002
Caldwell/Dillman[c]	TAES[d]	1961
Dillman	TAES	1965
Mac	TAES	1967
TAMF 201	TAES	1960
Nuturk	Unknown	Unknown
B 5128	NDSU[e]	1943
Rio	Unknown	Unknown
Viking	NDSU	Unknown

[a]AAFC- Agriculture and Agri-Food Canada
[b]NDSURF- North Dakota State University Research Foundation
[c] A cross between Caldwell 32 and Dillman
[d]TAES- Texas Agricultural Experiment Station
[e]NDSU- North Dakota State University

Table 3.2. Flax evaluation locations in Southeast Texas during 2008-2011.

Location	**Average Elevation above sea level (m)**	**Average Annual Precipitation (mm)**	**Average Annual Temperature (°C)**	**Soil Classification[a]**
College Station (30°36′N 96°18′W)	112	1000	20	Ships clay
McGregor (31°25′N 97°25′W)	211	894	17	San Saba clay
Yoakum (29°17′N 97°8′W)	111	1014	19	Tremona loamy fine sand

[a]Soil Survey Staff, NRCS, USDA, 2011.

Table 3.3. Average monthly rainfall and mean minimum and maximum temperature distribution at College Station, McGregor and Yoakum, Texas during 2008-2011.

	Location								
	College Station			**McGregor**			**Yoakum**		
Month	$T_{max.}$[a]	$T_{min.}$[b]	RF[c]	$T_{max.}$	$T_{min.}$	RF	$T_{max.}$	$T_{min.}$	RF
Jan.	15	2	10	13	0	4	18	3	6
Feb.	18	4	3	17	3	4	21	6	2
Mar.	22	8	8	21	8	15	25	9	8
Apr.	26	12	7	24	11	8	27	13	13
May	30	18	9	28	17	16	31	19	5
Jun.	34	22	7	33	22	8	35	22	10
Jul.	34	23	13	34	22	10	35	23	13
Aug.	36	23	7	35	23	4	36	23	5
Sep.	32	19	11	31	19	13	33	20	11
Oct.	28	12	10	26	12	13	30	12	5
Nov.	23	8	7	21	8	3	25	8	6
Dec.	16	3	6	15	1	3	19	3	4

Information adapted from (Wilson et al., 2007 and Yang et al., 2010).
[a] Tmax- Mean monthly maximum temperature in ˚C
[b] Tmin- Mean monthly minimum temperature in ˚C
[c] RF- Monthly average rainfall in cm.

The genotypes selected in the study represent different regions of the United States (North Dakota, South Dakota, and Texas) and Canada in which these genotypes were selected, developed and grown commercially. The Texas genotypes were developed between 1960 and 1980 by the Texas Agricultural Experiment Station. The seed of these genotypes were obtained from the USDA-ARS National Plant Germplasm Service. Seed was increased in the 2006-2007 in preparation for the research trial in 2007-2008. In 2009-2010 and 2010-2011 seasons, seed from the previous season was sieved and air cleaned after threshing, which was used for planting the following season. The lack of flax commercial production and active breeding programs since the 1980's has impaired the development of more recent varieties in Texas. The flax breeding programs in Texas between 1960 and 1980 was mostly dedicated to the development of varieties with cold tolerance. In most of the production regions of Texas, flax was grown as a fall season crop where cold injury was a major yield-limiting factor. The varieties selected for evaluation from North Dakota, South Dakota, and Canada are relatively new and developed recently for improved- yield, oil content, and quality.

3.2.1. Experimental design and treatments

The experimental design was a modified randomized complete block (RCBD) design with four replications. Treatments were composed of 20 genotypes (Table 3.1), which were assigned randomly in each replication to minimize the error due to soil heterogeneity. The same experimental design was used for all three locations in all three site-years. At each location, the experiment was planted on a different location within the same field each year.

3.2.2. Planting details and crop management

In 2008-2009, the flax experiment was only planted at the College Station location. The experiment was expanded to McGregor and Yoakum for the second and third years, 2009-2010 and 2010-2011, respectively. The experiments were planted in College Station on the 25th, 13th, and 16th of November in three consecutive years. The planting dates for McGregor were the 10th and 11th of November for 2009-2010 and 2010-2011, respectively.

The planting dates for Yoakum were November 5 and 22 for 2009-2010 and 2010-2011, respectively. However, in 2009-2010, the crop did not establish an acceptable stand at the Yoakum location because of poor emergence.

Management practices were similar in all locations in all years unless specified. Before planting, the soil was cultivated with a tandom disc and followed by a culti- packer. Weeds such as Morningglory (*Convolvulus arvensis*) and pigweed (*Amaranthus species*) were problematic at various stages of crop growth in spring. Application of Roundup @ 34 ml per liter of water controlled most of the pre-plant weeds at the initial stages of plant growth. The spray nozzles were Teejet 80-02 DG tips with 275 kPa pressure, to spray 140 liters ha^{-1}. At all locations, hand weeding was performed when necessary to minimize the weed competition. A pre-plant application of nitrogen at the rate of 56 kg ha^{-1} and phosphorous at the rate of 34 kg ha^{-1} was supplemented to the soil before planting at each location every year. The fertilizer was sprayed at 140 litersr ha^{-1} using the 110-03 TeeJet tips on a 9 m Remcor Boom sprayer. The seeding rate was 39 kg ha^{-1} and planted to a depth of 1.3 to 1.9 cm using small plot planter. During peak vegetative period, top dressing of nitrogen at the rate of 56 kg ha^{-1} was supplemented. The experimental units were 1.5 x 4.5 m plots and the inter row spacing was 20 cm. Biotic stresses due to pests and diseases were minimal at all locations during the three years of this trial.

3.2.3. Harvesting

The crop was harvested when 80-90% bolls turned brown and seed moisture was 8-12%. In College Station, the experiment was harvested on June 19, 12, and 6 for three consecutive years during 2008-2011, respectively. In McGregor, the experiment was harvested on June 5 and 2 during 2009-2010 and 2010-2011, respectively. In Yoakum, the experiment was harvested on June 10 in 2010-2011. The yield in kg ha^{-1} was assessed by multiplying the factor based upon the 1.5 x 4.5 m plot dimensions.

3.2.4. Statistical analysis

The statistical software SAS® 9.2 version (SAS Institute, 2008) was used for data analysis. Duncan's Multiple Range Test (α=0.05) was implemented in testing the significant difference between the varieties. To combine the data from multiple years, Bartlett's Test of Homogeneity for response variance was followed. The analysis of covariance (ANCOVA) procedure was followed to analyze the variation due to cold injury and weed pressure in 2009-2010 at McGregor.

Biplot analysis (GGE Biplot) was conducted to determine the genotype performance in all three tested locations (genotype by environment interaction). By using mean values of genotypes, a two-way matrix (rows and columns) was generated treating genotypes as entries and components as testers. The methodology suggested by Yan and Tinker (2006) was followed in interpreting the biplot results. The biplot can be explained by the following model:

$$Y_{ij} - \mu - \beta_j = \lambda_1 \xi_{i1} \eta_{j1} + \lambda_2 \xi_{i2} \eta_{j2} + \in_{ij}$$

where Y_{ij} = expected value of entry i and tester j, μ = grand mean, β_j = mean of all genotypes to j, λ_1= principle component(PC)1, ξ_{i1}= PC1 eigenvector of entry i, η_{j1}= PC1 eigenvector of tester j, λ_2= PC2, ξ_{i2}= PC2 eigenvector of entry i, η_{j2}= PC2 eigenvector of tester j, and $\in_{ij}$= residual of model associated with combinations of entry i and tester j.

3.3. Results and discussion

3.3.1. Cold injury ratings

Cold injury ratings for both College Station and McGregor during 2009-2011 are presented in Table 3.4. In Yoakum, cold injury ratings were not recorded in the 2010-2011 year due to poor emergence. During 2008-2009, the cold injury was minimal in College Station. During this cropping season, December 10 and 16 of 2008 recorded several hours below 0°C, but

never below -2°C. In 2009-2010, the lowest temperatures were recorded on December 4 and 5 of 2009 and January 8, 9 and 10 of 2010 and recorded several hours below -2°C at various occasions at below 6-leaf stage. In 2009-2010, the Texas genotypes Mac, Dillman, and Caldwell/Dillman showed significant cold tolerance compared to most of the North Dakota and Canadian genotypes ($p \leq 0.05$). Based on visual observation, the stand loss due to cold temperatures ranged from 10-30% depending on the genotype. However, the hypothesized cold tolerance of Texas genotypes was not observed in the yields due to subsequent recovery of all other genotypes by developing new tillers, which compensated for yield loss. Surprisingly, the genotype Pembina (North Dakota) showed the highest cold tolerance, followed by all Texas genotypes. Statistically, there was no significant ($P>0.05$) difference between Pembina and the Texas genotypes for the cold tolerance. Most of the Canadian and North Dakota genotypes showed cold susceptibility. AC Watson (Canadian) showed the highest cold susceptibility (visual rating 5). However, the variability (c.v. = 61%) in the cold injury ratings was so high that no significant differences were detected in the experiment. The Canadian and North Dakota varieties were developed for a May planting, thus these genotypes are not normally exposed to temperatures of this nature.

During 2010-2011, the relative advantage of Texas genotypes was prominent over Canadian and North Dakota varieties because of the severe cold injury. The temperatures were around -7°C for prolonged periods at the early stage of plant growth (2-4 leaf stage). All genotypes except the Texas genotypes were severely damaged and the mortality rate was up to 100% (Fig. 3.1).

In McGregor, during 2009-2010, all genotypes were severely affected by the cold injury including Texas genotypes. The cold tolerance of Texas genotypes was not prominent at McGregor during 2009-2010 because of temperatures below -7°C on Jan 8, 9, and 10 at the early stages of plant growth (2-4 leaf stage). Similar to College Station, Pembina showed the most tolerance to cold temperatures ($P>0.05$), followed by Nekoma (Table 3.4). Pembina is a North Dakota variety, with a pedigree of FP805 / SD8308 (N9301).

Table 3.4. Cold injury ratings in College Station and McGregor, TX. during 2009-2011.

	College Station		McGregor	
Genotype	**2009-2010**	**2010-2011**	**2009-2010**	**2010-2011**
Viking	0.50[a] cd[b]	4.50 a	5.00 a	5.00 a
B5128	4.00 a	5.00 a	5.00 a	5.00 a
Rio	3.50 ab	4.50 a	5.00 a	4.50 a
Caldwell/Dillman	0.50 cd	0.50 b	4.00 cd	1.00 b
Mac	0.50 cd	1.00 b	4.25 b-d	1.50 b
Dillman	0.50 cd	1.00 b	4.00 cd	2.00 b
TAMF201	0.50 cd	1.00 b	4.50 a-c	2.50 b
Nuturk	3.50 ab	5.00 a	5.00 a	2.00 b
AC Linora	2.75 a-c	5.00 a	5.00 a	5.00 a
Carter	3.75 ab	5.00 a	5.00 a	5.00 a
AC Carnduff	0.75 cd	3.50 ab	3.75 d	5.00 a
AC Emerson	1.50 b-d	5.00 a	5.00 a	5.00 a
Pembina	0.25 d	4.50 a	1.50 f	5.00 a
Nekoma	2.75 a-c	4.50 a	2.50 e	5.00 a
Lightning	3.75 ab	5.00 a	4.75 ab	5.00 a
York	3.25 ab	5.00 a	5.00 a	5.00 a
Prairie Blue	2.00 a-d	5.00 a	5.00 a	5.00 a
Prairie Thunder	3.25 ab	5.00 a	5.00 a	5.00 a
AC Mc.Duff	4.25 a	5.00 a	5.00 a	5.00 a
AC Watson	5.0 a	5.00 a	3.5 ab	5.00 a
Mean	2.3	4.0	4.3	4.4
CV[c] (%)	61.2	8.4	6.3	4.1

[a] Cold injury rating 0-5; 0- no injury and 5- complete mortality
[b] Numbers with distinct Duncan letters are significantly different at 0.05 probability levels
[c] Coefficient of variation

Fig. 3.1. Flax cold injury in College Station, Texas during 2010-2011.

Although the exact reason for partial cold tolerance of Pembina is unknown, parental cold tolerance is a possibility. However, the severity of cold injury was much higher in McGregor compared to College Station in 2009-2010. The subsequent recovery after prolonged cold temperatures at the McGregor location was low compared to College Station. In addition to the cold injury, weed pressure and poor emergence caused lower yield at McGregor. In 2010-2011, the cold injury damaged all other genotypes except the Texas genotypes. The temperatures were around -9°C for several hours during February 9 and 10 at stem extension stage. The extent of damage due to cold injury ranged from 10-100% plant mortality. Most of the varieties developed and adapted for North Dakota and Canada were susceptible to the cold temperatures. For example, North Dakota varieties such as Pembina, Nekoma, York, and Carter recorded 90-100% mortality rate and Canadian varieties such as AC Linora, AC Emerson, and AC Carnduff recorded 100% mortality due to severe cold injury.. The cold injury ratings in McGregor were consistent with the College Station ratings during 2010-2011 due to similar conditions at both locations.

Overall, the Texas genotypes showed a higher level of cold tolerance at both locations during 2010-2011 compared to all other genotypes. The Texas genotypes recorded cold injury ratings of ≤ 1 and ≤ 2.5 on a 1-5 scale at College Station and McGregor, respectively (Table 3.4). Most of the North Dakota and Canadian genotypes showed 100% complete mortality (cold injury rating of 5) (Fig. 3.2).

3.3.2. Flax yields and oil content

College Station

All twenty genotypes of flax were tested for their yield potential and oil yield during 2008-2011. The results indicated that during 2008-2009, genotype had significant effect on the yield of flax (Pr <.0001). The model explained about 67% of the variation due to genotype and replication. The remaining 33% of unexplained variation (error) contributed toward environmental and biological factors. The mean flax yield for College Station during 2008-2009 was 1907 kg ha^{-1} and yield ranged from 1299 to 2496 kg ha^{-1}. During 2009-2010, the

Fig. 3.2. Flax cold injury at McGregor, Texas during 2010-2011.

results also suggested that the genotype had significant effect on flax yield (Pr <.0001). However, during 2009-2010, the cold injury was more severe than 2008-2009. The average yield for the location during the year 2009-2010 was 1673 kg $ha^{-1}$and yield ranged from 1237 to 2406 kg ha^{-1}. The cold injury significantly affected the stand count (data not shown) in 2009-2010. However, tiller production at the later growth stages, facilitated by the adequate moisture in the soil, compensated for the stand loss. As a result of increased tiller production, the yield in the second year was similar to 2008-2009.

Based on the Bartlett test of homogeneity (Pr>0.42), the two years were combined. The genotype was treated as fixed and year as a random effect. The ANOVA and expected sums of squares are presented in the Table 3.5. The year had no significant effect on the yield of flax due to the compensatory effect of excessive tillers. The genotype (Pr < .0095), replication within the year (Pr <.0001), and the interaction of the year with genotype (Pr <.0017) showed significant effect on the yield. The interaction term between the year and genotype probably indicated the different environmental factors in the two site-years. The two-year mean yield was 1790 kg ha^{-1} and yield ranged from 1363 to 2451 kg ha^{-1} for College Station.

During 2008-2010, York recorded the highest mean yield with 2451 kg ha^{-1} (Table 3.6). Nekoma ranked second with a two-year average yield of 2261 kg ha^{-1}. However, there was no statistical significance between York and Nekoma. Both of these highest yielding genotypes were developed and released by NDSU. Prairie Thunder (Canadian genotype) ranked third after York and Nekoma. The yield potential of the Texas genotypes was low compared to most of the Canadian and North Dakota genotypes due to mild temperatures during 2009-2010. Most of the tillers in the Texas genotypes were non-productive and produced at the later stages of plant growth. Limited moisture lowered the number of productive tillers in all Texas genotypes. However, there appeared to be no correlation between cold injury and yield due to the subsequent recovery of plants. The coefficients of variations for two years were 14.01% and 14.17% respectively (Table 3.6).

Table 3.5. Mixed model combined analysis of variance for flax genotype evaluation at College Station during 2008-2010.

Source	Adjusted DF	Type III Sum of squares	Mean Squares	F-value	Pr>F	Type III Expected Mean Square
Genotype	19	2956.24	155.59	3.06	0.0095**	Var(Error) + 4 Var(year*genotype) + Q(treatment)
Error $_{genotype}$	19	967.56	50.92	-	-	Var(year*genotype)
Rep (year)	6	1278.45	213.07	10.37	<.0001***	Var(Error) + 20 Var(rep(year))
Error $_{rep(year)}$	114	2343.11	20.55	-	-	Var(error)
Year	1	52.25	52.25	0.21	0.6560 ^{ns}	Var(Error) + 4 Var(year*genotype) + 20 Var(rep(year)) + 80 Var(year)
Error $_{year}$ (adjusted)	7.69	1872.06	243.45	-	-	Var(rep(year)) + Var(year*genotype) - Var(Error)
Year*Genotype	19	967.56	50.92	2.48	0.0017***	Var(Error) + 4 Var(year*genotype)
Error $_{year*genotype}$	114	2343.11	20.55	-	-	Var(error)

** Significant at P< 0.01
*** Significant at P< 0.001
^{ns} Not significant at P< 0.0

Table 3.6. Mean yield of flax genotypes in College Station, TX during 2008-2011.

	Yield, kg ha^{-1}				
Variety	**2008-2009**	**2009-2010**	**2010-2011**	**Two-Year Mean (2008-2010)**	**Three-Year Mean[b]**
York	2496	2406	132	2451 a[a]	1678
Nekoma	2292	2246	340	2269 a-c	1626
Pembina	2139	2017	419	2078 b-d	1525
PrairieThunder	2413	1685	-	2049 b-d	1366
Carter	2224	1823	104	2024 b-d	1384
AC Linora	1931	2030	-	1981 b-d	1321
Prairie Blue	2216	1593	146	1905 de	1318
AC Carnduff	2067	1656	356	1861 d-e	1359
Caldwell/Dillman	2120	1544	928	1832 d-g	1531
AC Lightning	1771	1715	-	1743 d-g	1162
Viking	1788	1658	362	1723 d-g	1269
AC McDuff	1575	1862	-	1719 d-g	1146
Rio	1658	1757	426	1708 d-g	1281
Nuturk	1707	1579	629	1643 d-g	1305
Dillman	1716	1379	735	1547 d-g	1277
Mac	1799	1292	613	1545 d-g	1234
AC Emerson	1779	1237	-	1508 d-g	1005
AC Watson	1599	1279	-	1439 d-g	959
B 5128	1545	1272	-	1408 g	939
TAMF 201	1299	1427	771	1363 g	1166
Mean	1906	1672	458	1789	1345
CV[c] (%)	14.0	14.2	64.7	14.1	-

[a]Means with same Duncan letters represent no statistical difference at 0.05 significance level
[b]Mean yield of three-year, not represented by letters due to heterogeneity of variance
[c] Coefficient of variation

In 2010-2011, the severe cold injury decreased the yield of most of the genotypes significantly. The Texas genotypes showed relative yield advantage in 2010-2011. Caldwell/Dillman showed the highest yield in this cropping season, 928 kg ha^{-1}, followed by TAMF 201, 771 kg ha^{-1}. York, Pembina, and Nekoma yielded less than 450 kg ha^{-1}.

Three year mean yields are also reported in the Table 3.6. The significance of the three-year mean yield was not tested because of the heterogeneity of variance (statistically different variances among the years of testing). Most of the heterogeneity was introduced from the cold injury in the third cropping year. However, the three-year mean yield indicated that York had the highest yield (1678 kg ha^{-1}), followed by Nekoma (1626 kg ha^{-1}) and Caldwell/Dillman (1531 ka ha^{-1}). The relative yield advantage of Texas genotypes developed in 1960-1970 was prominent only in the 2010-2011, where cold temperatures impacted growth. In the years where freezing temperatures were not an issue, the yield potential of most Texas genotypes was lower than the non-Texas genotypes. Thus, the three-year mean for most of the Texas genotypes was low. For example, the yield potential of Mac, Dillman, and TAMF 201 in 2008-2009 and 2009-2010 (mild years) was less than the North Dakota genotypes (Table 3.6).

The two-year mean test weight and oil percent for College Station is presented in Table 3.7. The results indicate that Caldwell/Dillman recorded the highest test weight (67.1 kg haL^{-1}), followed by AC McDuff (66.2 kg haL^{-1}) and York (64.9 kg haL^{-1}). However, there was no significant difference between those ($P>0.05$) genotypes.

The oil content was highest in AC McDuff (42.8% w/w) followed by AC Lighning (42.7% w/w). However, there was no statistical difference between the oil percent of AC McDuff and AC Lightning. There was no correlation observed between the yield potential and oil content. The location mean and range for oil content was 39.5% and 37.1 to 42.8%, respectively. The oil contents were not analyzed for McGregor and Yoakum due to the lack of consistent measurable yields in all cropping seasons.

Table 3.7. Mean test weight and oil content of flax in College Station, TX. in 2008-2011.

Variety	Test Weight (kg haL$^{-1)}$	Oil Percent, % (w/w)
Caldwell/Dillman	67.1 a[a]	38.4 d-g
AC McDuff	66.2 ab	42.8 a
York	64.9 abc	38.3 e-g
Nuturk	64.8 abc	38.6 c-g
PrairieThunder	64.7 abc	40.8 b
TAMF 201	63.9 abc	39.8 b-e
Pembina	63.4 abc	40.2 bc
AC Carnduff	63.0 abc	39.2 b-f
AC Emerson	62.9 abc	38.0 fg
Rio	62.9 abc	37.3 g
Carter	62.6 abc	40.8 b
B 5128	62.0 abc	37.1 g
Dillman	62.0 abc	39.2 b-f
Mac	61.7 abc	39.7 b-e
Prairie Blue	61.3 abc	40.0 b-d
AC Watson	59.8 abc	38.7 c-g
AC Lightning	59.5 abc	42.7 a
Viking	59.3 bc	37.8 g
Nekoma	59.1 bc	40.2 bc
AC Linora	57.4 c	38.6 c-g
Mean	62.4	39.4
CV[b](%)	1.9	2.5

[a] Means with same Duncan letters represent no statistical difference at 0.05 significance level
[b] Coefficient of variation

McGregor

The yield results of flax genotypes for McGregor and Yoakum are presented in Table 3.8. Flax yield potential at McGregor for the crop year 2009-2010 was limited by cold injury occurring at the early growth stage (2-4 leaf stage). The germination percentage at McGregor was very low in the beginning of crop year and the subsequent cold injury lowered the plant stands even more (data not shown) (Figure 3.2). In the analysis, the stand count was used as co-variate to adjust the yield potential of each genotype for the year 2009-2010. All Texas genotypes yielded relatively high and Caldwell/Dillman yielded the highest (1431 kg ha^{-1}) compared to all other genotypes. Most of the Canadian genotypes yielded low or none due to the cold susceptibility. In 2010-2011, Caldwell/Dillman yielded highest (862 kg ha^{-1}) and the results were consistent with the previous year. All Texas genotypes yielded comparatively higher in both site-years at McGregor (Table 3.8).

The data was not combined across the years because of the heterogeneity of variance (Bartlett test of homogeneity, $p>.0001$). However, the mean yield from two years is reported in the Table 8. The mean two-year yield was highest for Caldwell/Dillman (1147 kg ha^{-1}), followed by Nekoma (839 kg ha^{-1}) and York (806 kg ha^{-1}). It appeared to be a direct correlation between the cold tolerance and yield potential.

Yoakum

In the first year (2008-2009), the flax failed to emerge in Yoakum. The soil conditions and severe drought caused the poor emergence. In 2010-2011, the emergence was low for all genotypes, followed by severe drought and weed competition that reduced the stands even further. Caldwell/Dilllman and Nekoma yielded highest with 577 and 553 kg ha^{-1}, respectively. The yields were very low compared to the other two locations with a yield range of 95 and 577 kg ha^{-1}. Unlike College Station, flax was not well adapted to this region of Texas due to untimely precipitation and unfavorable soil conditions in the tested years.

Table 3.8. Mean yield of flax genotypes at McGregor and Yoakum during 2009-2011.

	Yield (kg ha$^{-1)}$			
	McGregor			Yoakum[b]
Variety	2009-2010	2010-2011	Two-year mean[a]	2010-2011
Caldwell/Dillman	1431	862	1147	577 a
Nekoma	1387	291	839	553 a
York	1335	277	806	534 a
Pembina	1361	217	789	523 ab
Nuturk	895	594	744	510 ab
Dillman	934	510	722	510 ab
Mac	820	561	691	446 ab
AC Carnduff	1166	0	583	394 ab
TAMF 201	653	454	553	355 ab
Prairie Blue	1078	0	539	351 ab
Rio	429	370	400	150 ab
Carter	725	0	363	335 ab
Viking	275	389	332	316 ab
AC McDuff	606	0	303	270 ab
AC Emerson	453	0	226	275 ab
AC Linora	362	0	181	238 ab
B 5128	337	0	168	175 ab
AC Lightning	-	-	-	95 b
AC Watson	-	-	-	-
PrairieThunder	-	-	-	-
Mean	838	266	552	387
CV[c] (%)	74.2	12.2	7.1	40.0

[a] Means with no Duncan letters represent heterogeneity of variance
[b] Means with same Duncan letters represent no statistical difference at 0.05 significance level; means were adjusted based on stand counts in McGregor during 2009-2010
[c] Coefficient of variation

3.3.3. Biplot analysis

Biplot analysis of yields at the three target environments (College Station, McGregor, and Yoakum) indicated that the polygon was partitioned into two mega environments (Fig. 3.3). The first mega environment included College Station and McGregor. In general, environments of College Station and McGregor were largely dissimilar in many aspects, but similar climate (cold injury, rainfall) and crop management (fertilizers, weed management) in those tested site-years (2008-2011) caused the two locations to be classified into one mega environment. Yoakum was classified into second mega environment as this location had different characteristic growth conditions.

The best genotype for a particular location or mega environment is based on the presence and absence of a genotype on the vertices of polygon. For example, Caldwell/Dillman and Nekoma had higher yields in College Station and McGregor as they are located on the vertices of polygon, followed by York and Pembina (falls on the line of polygon in order). Caldwell/Dillman had consistently higher yields in College Station and McGregor because of the prevalence of cold temperatures in two out of three years, which coincide with the native breeding environment. Nekoma, York, and Pembina were the prominent genotypes developed for May planting in North Dakota and had moderate tolerance to cold injury. Even though, other Texas genotypes (Mac, Dillman, and TAMF 201) showed significant cold tolerance, low yield potential caused low yield in College Station and McGregor. Most of the Canadian genotypes showed lower yield in the first mega environment due to lack of cold tolerance at both locations. Surprisingly, in the second mega environment (Yoakum), Rio and AC McDuff had higher yield. However, the limited data (one year data) for this location needs to be considered before making any recommendations.

All Texas genotypes showed relative cold tolerance compared to North Dakota and Canadian genotypes even though this did not always translate into the final yield. The main reason for relative cold tolerance of Texas genotypes can be explained by the selection within this environment. Flax was grown as a fall season crop in southeast Texas, and

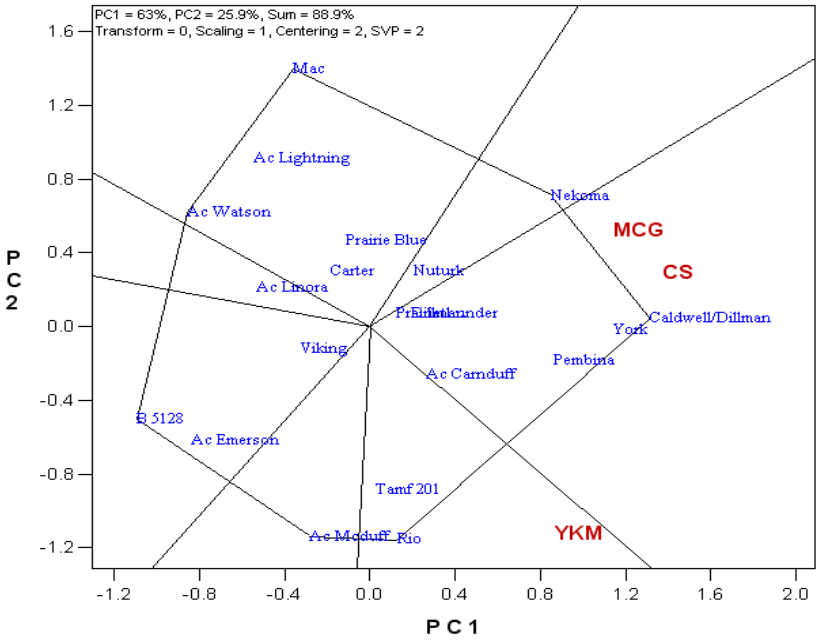

Fig. 3.3. Biplot analysis of tested genotypes of flax at College Station (CS), McGregor (MCG), and Yoakum (YKM) during 2008-2011. Ac=AC; Tamf 201= TAMF 201.

required cold tolerance to survive the freezing temperatures in December, January and February. However, irrespective of the genotype used, severe cold injury at the early two-leaf stage can be detrimental to the survival of flax (Harrington, 1936). This was evident from the cold injury ratings in McGregor during 2009-2010. Modification of planting date to avoid the coincidence of young plants with peak cold temperatures is a key to the production of flax in southeast Texas. Based on this information, planting in mid-October is ideal for flax production in southeast Texas. Planting too early in the season is not desirable because of the coincidence of low temperatures with the peak flowering and pollination in March. The relative advantage of Texas genotypes over North Dakota and Canadian genotypes was prominent in extreme cold temperatures rather than moderate temperatures. For example, all Texas genotypes yielded high compared to other prominent varieties in 2010-2011 at both College Station and McGregor. North Dakota and Canadian varieties were very well adapted to non-cold flax growing regions environments, as they were selected and grown for May planting.

Flax is well adapted to College Station due to better establishment within this trial site and more favorable growth conditions compared to McGregor and Yoakum. However, considering historical production of flax near Corpus Christi, flax can be grown in Yoakum with better management and soil conditions. In two out of three tested years, mean flax yield was 1790 kg ha^{-1} in College Station, which was approximately 500 kg ha^{-1} more than the national average in 2007. Due to absence of severe cold temperatures in two out of three site-years, York and Nekoma (North Dakota genotypes) yielded the highest. However, cold injury in 2010-2011 caused all North Dakota genotypes to yield poorly. All Texas genotypes yielded well in 2010-2011 in both McGregor and College Station. The Caldwell/Dillman cross (Texas genotype) yielded consistently high under cold temperatures in College Station and McGregor as indicated in Fig 3.1. Even though all Texas genotypes have some form of cold tolerance, poor yield potential limits the suitability of these genotypes for commercial production. The future task for flax breeding programs is to improve the yields in Texas by transferring cold tolerance from the Texas genotypes to high yielding genotypes.

3.4. Conclusions

The results from evaluation of different genotypes in three locations of southeast Texas suggested that all Texas genotypes showed relative cold tolerance compared to other genotypes. Flax was grown as a fall season crop in southeast Texas (Atkins et al, 1963), where the winter-kill was common (Omran, 1968). Considering the winter-kill of flax during fall season, flax breeding program in 1960-1970's were dedicated to develop genotypes suited to plant in fall season. All Texas genotypes that were selected in cold environments survived well, especially in 2010-2011 in both College Station and McGregor. The temperature was below -7°C for several hours at the growth stage below 6- leaf stage both at College Station and McGregor during 2010-2011, which was 5°C below the temperature (-1.7°C) reported by Rhavitin (1935) as the threshold cold tolerance of flax. Harrington (1936) reported the cold tolerance of flax above two-leaf stage. This was evident from current research that at freezing temperatures below -7°C, irrespective of growth stage, damaged all flax genotypes except cold tolerant Texas genotypes. Caldwell/Dillman cross (Texas genotype) was highly adapted to cold environments, being selected for Texas environments. Whereas all North Dakota and Canada genotypes were developed for spring planting and required no cold tolerance in those genotypes. The North Dakota and Canadian genotypes were improved varieties with high yield potential in non-cold environments and Texas genotypes had some level of cold tolerance. Selection of the cold tolerance trait from Texas genotypes and introgression into modern, high yielding varieties should provide a significant advancement in flax development in south Texas. In south Texas, flax was very well adapted to the area surrounding College Station with a mean yield of 1345 kg ha^{-1}, which was comparable to the state average yield of North Dakota in 2011 (USDA-NASS, 2011). However, in general, the cropping season of flax in Texas was approximately 1.5 months higher than the cropping season in North Dakota and other major producing states of U.S. due to differences in accumulation of growing degree days. Three-year average of College Station was about 100 kg ha^{-1} higher than the national average and two-year mean was 500 kg ha^{-1} higher than the national average in 2011(USDA-NASS, 2011). The College Station location had a maximum yield of about 2500 kg ha^{-1}, which was a double the yield

reported by Hodges et al. (1970). The current research results showed that the flax adaptability was limited to McGregor and south through College Station to Coastal Bend. In McGregor and north, cold injury was the major limiting factor for the flax production. In Yoakum, the emergence of flax was a limiting factor due to poor soil conditions. However, Atkins et al. (1963) reported that most of the flax production in Texas during 1930-1960 was concentrated north of Corpus Christi, along the coastal bend of Texas. It is also highly possible that the failure of flax in Yoakum is due to site-specific conditions and should not generalize the conclusions to entire south Texas. AC McDuff recorded highest oil content in College Station with a location average of about 40%. Assuming the historical flax acreage 133,198 ha from 1949 (USDA-NASS, 2011) and current maximum yield potential of 2500 kg ha^{-1} with 40% oil content, it would be equivalent to 144 million liters of oil. Therefore, flax is a potential biodiesel oil seed crop for southeast Texas.

CHAPTER IV

THE ASSOCIATION OF FLAX YIELD AND ITS COMPONENTS IN SOUTHEAST TEXAS BY USING PATH COEFFICIENT AND BIPLOT ANALYSES

4.1. Introduction

Flax (*Linum usitatissimum* L.) is a multi-purpose oilseed crop, originated in Mediterranean and Southwest Asia (Millam et al., 2005). This crop is known to have many industrial and health benefits (Lay et al., 1989; Stitt, 1990; Domier et al, 2000). World flax production is mostly concentrated in Canada, China, U.S.A., Russian Federation, Ethiopia, and India with the total production of 1.9 billion kg in 2010 (Food and Agriculture Organization, 2010). Canada was a leading nation in flax production in 2010 with about 0.42 billion kg of linseed production, followed by China with 0.35 billion kg (Food and Agricultural Organization, 2009). The United States was the third largest producer of flax with about 0.23 billion kg linseed production. Due to increasing interest in biofuels, flax is being considered as a potential biofuel crop in the U.S. and other regions of the world.

The effect of various components on yield depends largely on the environment and the type of elements (yield components) considered for yield estimation (Heinrich, 1983). The relative contribution of various components towards overall yield is site-specific and depends on numerous biotic and abiotic factors at a given location (Giunta, 1993; Tivoli, 1996).

Identifying the different yield components of a crop and selection for the most important yield-contributing components is a major step in the process of breeding for increased yield (Grafius, 1960). Significant research was conducted in many crops to establish the important yield components. Knott and Talukdar (1971) concluded that selection for increased kernel weight could improve wheat yield significantly. On the other hand, McNeal et al. (1978) determined that kernel weight and kernel number per spike were two

important selection characteristics for yield improvement of wheat. Dokuyucu and Akkaya (1999) demonstrated that the number of heads m^{-2}, grain weight per head, and number of grains per head maybe used for selection criteria for achieving higher yield in wheat. Path coefficient analysis conducted by Pandey and Torrie (1973) concluded that selection for pods per unit area and seeds per pod would improve the yields of soybean. Heinrich et al. (1983) observed that breeding for seeds per head and seed weight would result in higher yields in grain sorghum.

4.1.1. Yield components of flax

Dillman and Brismade (1938) reported that flax yield was not influenced by decreasing seed rates due to compensatory effect of increases in boll number. This fact was also supported by subsequent studies (Blackman and Bunting, 1954; Bothun and Nalewaja, 1965). Klages (1932) and Blackman and Bunting (1954) concluded that number of bolls per unit area was the most important factor affecting the yield of flax. They also reported that stand density had no effect on the boll number per unit area and seed number per boll. However, Diepenbrock and Iwersen (1989) reported that flax can compensate for low stand densities by increasing the number of fertile tillers and capsules. For spring-sown seed flax, there is less possibility of compensation due to the shortened vegetative phase (D'Antuono and Rossini, 1994). Albrechtsen and Dybing (1973) found that there were no significant yield differences for flax stands ranging from 100 to 700 plants m^{-2} and increase in the number of capsules per plant compensate the lower stand densities for seed yield. Casa et al. (1999) reported that high plant density significantly decreased the number of capsules per plant ($r=-0.73^{**}$) and seeds per plant ($r=-0.73^{**}$). Albrechtsen and Dybing (1973) also reported that there were significant negative correlations between seed size and number of bolls per area or number of seeds per boll. They also indicated that the indirect negative effect of seed size negates the positive effect of seeds per boll on the overall oil yield. Rahimi et al. (2011) concluded that capsule number ($r=0.98^{**}$), primary branch per plant ($r=0.85^{**}$), and 1000 seed weight ($r=0.90^{**}$) had significant positive effects on seed yield of flax. Similar results of positive effects between seed yield, capsule number, and number

of primary branches were indicated in numerous studies (Basu and Bose, 1976; Can et al., 2001, 2003; Kaynak, 1998). Moreover, several studies also concluded that pod number per plant and number of seeds per capsule had significant direct effects on the seed yield of flax (Vijayakumar and Rao, 1975; Nie et al., 1995).

This particular study evaluates the association between the tiller number, number of pods per tiller, number of seeds per pod, seed weight, and overall yields for three different locations in Texas. The main objectives of the study were to determine the association between the yield and its components in three locations of southeast Texas.

4.2. Materials and methods

4.2.1. Experimental design

The experimental design was a randomized complete block design (RCB) with twenty genotypes and four replications. This experiment was conducted in three locations (Table 4.1) during two years (2009-2011). The experimental units were 1.5 x 4.5 m plots and the inter row spacing was 20 cm. Due to stand establishment issues in 2009-2010, the data was not collected in the Yoakum location.

4.2.2. Planting details and important management practices

The experiments were planted in College Station on the 13, and 16 of November in 2009-2010 and 2010-2011, respectively. The planting dates for McGregor were the 10 and 11 of November for 2009-2010 and 2010-2011, respectively. The planting dates for Yoakum were November 5 and 22 for 2009-2010 and 2010-2011, respectively. However, in 2009-2010, the crop did not establish an acceptable stand at the Yoakum location because of poor emergence.

Management practices were similar in all locations in all years unless specified. Before planting, the soil was cultivated to fine tilth with a tandom disc and culti-packer. Weeds such as Morning glory (*Convolvulus arvensis*) and Pigweed (*Amaranthus palmeri*) were

problematic at various stages of plant growth in spring. Application of Roundup @ 34 ml L^{-1} of water controlled most of the pre-plant weeds during the initial stages of plant growth. The spray nozzles were Teejet 80-02 DG tips with 125 kPa pressure on a Remcor boom sprayer, to spray 140 L ha^{-1}. At all locations, hand weeding was performed when necessary to minimize the weed competition. A pre-plant application of nitrogen at the rate of 56 kg ha^{-1} and phosphorous at the rate of 34 kg ha^{-1} was supplemented to the soil before planting at each location every year. The fertilizer was sprayed at 140 L ha^{-1} using the 110-03 TeeJet tips on a 9 m with the same sprayer as listed above. The seeding rate was 39 kg ha^{-1} and planted to a depth of 1.3 to 1.9 cm using a Hege 500 plot planter. During peak vegetative period, top dressing of nitrogen at the rate of 56 kg ha^{-1} was supplemented. Biotic stresses due to pests and diseases were minimal at all locations in all three site-years.

4.2.3. Harvesting

The crop was hand-harvested when 80-90% bolls turned brown and seed moisture was 8-12%. In College Station, the experiments were harvested on June 12, and 6 in 2010 and 2011, respectively. In McGregor, the experiments were harvested on June 5 and 2 in 2010 and 2011, respectively. In Yoakum, the experiment was harvested on June 10 in 2011.

4.2.2. Data collection

Various components that contributed to overall yield of flax were assessed. From each plot, ten productive tillers were selected randomly and hand harvested with pods. A productive tiller was defined as the stem or branch of stem that had mature pods at the time of tiller harvest and were expected to contribute to yield. The tiller number in this experiment denotes productive tillers. The pods were separated from each tiller and counted for sample pod number. The pods were thrashed with hand and cleaned the seed with Bates Laboratory Aspirator (HT McGill, 66-4554 model). The seed was weighed with Scout Pro scale (Ohaus manufactures, SP-602 model) for total sample weight. The seed number was counted for the entire sample using Totalize Unit seed counter (International Marketing and Design Corp., model 750-2). To estimate the single seed weight, the seed weight of each sample was

Table 4.1. Elevation, precipitation, temperature and soil classification for the flax evaluation locations in College Station, McGregor and Yoakum, Texas in 2009-2011.

Location	**Average Elevation above sea level (m)**	**Average Annual Precipitation (mm)**	**Average Annual Temperature (°C)**	**Soil Classification[a]**
College Station (30°36′N 96°18′W)	112	1000	20	Very-fine, mixed, active, thermic Chromic Hapluderts
McGregor (31°25′N 97°25′W)	211	894	17	Fine, montmorillonitic, thermic Udic Haplusterts.
Yoakum (29°17′N 97°8′W)	111	1014	19	Clayey, mixed, active, thermic Aquic Arenic Paleustalfs

[a]Soil Survey Staff, NRCS, USDA, 2011

divided by the seed number of the entire sample. The number of tillers per plot was estimated by dividing whole plot seed yield by seed weight per tiller. Number of pods per tiller was calculated by dividing sample pod number by ten tillers. Seed number per pod was calculated by dividing seed number per sample by number of pods per sample. The total yield is equivalent to the multiplication product of pods per tiller, seed per pod, single seed weight, and tiller number.

4.2.3. Statistical analyzes

The data was analyzed by using SAS (SAS Institute Inc., 2008) for Pearson correlation coefficient and path coefficient analysis. Path coefficient analysis for partitioning of yield components into direct and indirect effects was performed by following the methodology of Cramer et al. (1999). In addition to the total Pearson correlations between yield and yield components, path coefficients were determined to understand the direct and indirect effects among different yield components and yield. GGE biplot software was used in producing the genotype-by-trait figures (Yan and Kang, 2003) to see the relationship among different yield components. By using mean values of genotypes, a two-way matrix (rows and columns) was generated treating genotypes as entries and components as testers. The methodology suggested by Yan and Tinker (2006) was followed in interpreting the biplot results. The biplot can be explained by the following model:

$$Y_{ij} - \mu - \beta_j = \lambda_1 \xi_{i1} \eta_{j1} + \lambda_2 \xi_{i2} \eta_{j2} + \in_{ij}$$

where Y_{ij} = expected value of entry i and tester j, μ = grand mean, β_j = mean of all genotypes to j, λ_1= principle component (PC) 1, ξ_{i1}= PC1 eigenvector of entry i, η_{j1}= PC1 eigenvector of tester j, λ_2= PC2, ξ_{i2}= PC2 eigenvector of entry i, η_{j2}= PC2 eigenvector of tester j, and $\in_{ij}$= residual of model associated with combinations of entry i and tester j (Yan and Tinker, 2006).

4.3. Results and discussion

4.3.1. Pathcoefficient analysis

Seed Yield

The results from Pearson correlation coefficient analysis showed that seed yield had the positive correlation with productive tiller number in all locations (College Station ($r=0.72$, $p<0.01$), McGregor ($r=0.88$, $p<0.01$), and Yoakum (($r=0.67$, $p<0.05$)), including all locations combined ($r=0.87$, $p<0.01$) (Table 4.2). Seed yield showed negative correlation with pods per tiller in College Station ($r=-0.50$, $p<0.05$), McGregor ($r=-0.79$, $p<0.01$), and combined ($r=-0.71$, $p<0.01$). In Yoakum, seed yield showed positive non-significant correlation with pods per tiller ($r=0.45$, $p< 0.05$). Seed per pod and seed weight had not correlations with ($p<0.05$) seed yield in all locations, except that seed weight was significantly correlated with seed yield in McGregor ($r=-0.55$, $p< 0.05$).

A direct effect in path coefficient analysis can be defined as effect of independent variable that correlate directly to a dependent variable in the absence of all other independent variables. It was denoted in the Table 4.3 by underline. An indirect effect can be defined as effect of all other independent variables on direct independent variable, there by affecting the dependent variable. A resultant total Pearson correlation of the direct effect is the additive effect of direct and indirect effects on the dependent variable. For example, the direct effect of pods per tiller (direct independent variable) on seed yield (dependent variable) is 1.63 and indirect effects of seed per pod, seed weight, and tiller number on pods per tiller that ultimately affect seed yield were -0.45, 0.05, -1.73, respectively. The resultant additive effect of direct and indirect effects (1.63, -0.45, 0.05, and -1.74) is a total Pearson correlation between pods per tiller and seed yield, which is -0.50.

The results from path coefficient analysis showed that the positive direct effect of tiller number on yield was negated mostly by the indirect effect of pods per tiller except in McGregor (Table 4.3). However, the positive direct effect of tiller number on yield was

Table 4.2. Pearson correlation coefficients for flax yield and its components in College Station, McGregor, Yoakum and in all locations combined during 2009-2011.

Trait	Pods/tiller	Seed/pod	Seed wt.[a]	Tiller no.[b]	Yield
College Station					
Pods/tiller	1.00	-0.47	0.12	-0.85**	-0.50*
Seed/pod	-	1.00	-0.43	0.14	0.26
Seed wt.	-	-	1.00	-0.19	-0.15
Tiller no.	-	-	-	1.00	0.72**
Yield	-	-	-	-	1.00
McGregor					
Pods/tiller	1.00	-0.44	0.76**	-0.77**	-0.79**
Seed/pod	-	1.00	-0.63**	0.21	0.36
Seed wt.	-	-	1.00	-0.63**	-0.55*
Tiller no.	-	-	-	1.00	0.88**
Yield	-	-	-	-	1.00
Yoakum					
Pods/tiller	1.00	-0.55*	-0.09	-0.21	0.45
Seed/pod	-	1.00	0.21	-0.35	-0.41
Seed wt.	-	-	1.00	-0.16	0.11
Tiller no.	-	-	-	1.00	0.67*
Yield	-	-	-	-	1.00
Combined					
Pods/tiller	1.00	-0.27 [NS]	0.56*	-0.88**	-0.71**
Seed/pod	-	1.00	-0.63**	0.07	0.11
Seed wt.	-	-	1.00	-0.47	-0.31
Tiller no.	-	-	-	1.00	0.87**
Yield	-	-	-	-	1.00

*P ≤ 0.05 level
**P ≤ 0.01 level
[NS] Statistically not significant
[a] Seed Weight
[b] Productive tiller number

large enough to offset the negative indirect effect of pods per tiller, and resulted in positive effect of tiller number on yield. Likewise, the negative indirect effects of tiller number and seed per pod on yield offset the direct positive effect of pods per tiller and resulted in negative total correlation between yield and pods per tiller. In most of the locations, the direct effects of seed per pod and seed weight were not large enough, resulted in non-significant correlations with seed yield.

Pods per tiller

The results from Pearson correlation coefficient analysis showed that pods per tiller trait had negative correlation with tiller number in College Station ($r=-0.85$, $p<0.01$), McGregor ($r=-0.77$, $p<0.01$), and locations combined ($r=-0.88$, $p<0.01$) (Table 4.2). Seed per pod had no correlations with ($p<0.05$) pods per tiller all locations, except in Yoakum ($r=-0.55$, $p<0.05$). Seed weight showed positive correlation with pods per tiller in McGregor ($r=0.76$, $p<0.01$) and locations combined ($r=0.56$, $p<0.05$).

The results from path coefficient analysis showed that pods per tiller had direct positive effect on yield in all locations except McGregor. However, the direct positive effect of pods per tiller was negated by indirect effect of tiller number, resulted in negative total correlation of pods per tiller on seed yield except in Yoakum. In all locations, negative correlation between tiller number pods per tiller was a common.

Seed per pod

The results from Pearson correlation coefficient analysis showed that seed per pod trait had no correlations ($p<0.05$) with the most of the yield components including yield, except seed weight in McGregor and locations combined ($r=-0.63$, $p<0.01$) and pods per tiller in Yoakum ($r=-0.55$, $p<0.05$) (Table 4.2).

The results from path coefficient analysis showed that seed per pod had direct positive effect on yield in all locations, especially large in College Station. However, the direct

Table 4.3. Direct and indirect effects of flax yield components and total correlation with flax seed yield in College Station, McGregor, Yoakum and all locations combined during 2009-2011.

Component	Pods/tiller	Seed/pod	Seed wt.[a]	Tiller no.[b]	Nobs[c]	Total
College Station						
Pods/tiller	1.63[d]	-0.45	0.05	-1.74	16	-0.50
Seed/pod	-0.77	0.96	-0.20	0.28	16	0.26
Seed wt.	0.19	-0.41	0.47	-0.39	16	-0.15
Tiller no.	-1.38	0.13	-0.09	2.05	16	0.72
McGregor						
Pods/tiller	-0.33	-0.12	0.28	-0.62	16	-0.79
Seed/pod	0.14	0.28	-0.23	0.17	16	0.36
Seed wt.	-0.25	-0.18	0.37	-0.50	16	-0.55
Tiller no.	0.25	0.06	-0.23	0.80	16	0.88
Yoakum						
Pods/tiller	0.90	-0.21	-0.03	-0.22	16	0.45
Seed/pod	-0.49	0.39	0.06	-0.36	16	-0.41
Seed wt.	-0.09	0.08	0.28	-0.17	16	0.11
Tiller no.	-0.19	-0.14	-0.04	1.04	16	0.67
Combined						
Pods/tiller	0.35	-0.08	0.16	-1.15	16	-0.71
Seed/pod	-0.10	0.29	-0.19	0.10	16	0.11
Seed wt.	0.20	-0.19	0.30	-0.62	16	-0.31
Tiller no.	-0.31	0.02	-0.14	1.30	16	0.87

[a]Seed Weight
[b] Productive tiller number
[c]Number of observations considered for analysis
[d]Underline represents direct effect of a trait on yield

positive effect of seed per pod was negated by indirect effect of pods per tiller in College Station and Yoakum.

Seed weight

The results from Pearson correlation coefficient analysis showed that seed weight trait had negative correlation with seed per pod ($r=-0.63$, $p<0.01$) in both McGregor and locations combined. Seed weight had t positive correlation with pods per tiller ($r=0.76$, $p<0.01$) and negative correlation with tiller number ($r=-0.63$, $p<0.01$) and seed yield ($r=-0.55$, $p<0.05$) in McGregor (Table 4.2).

The results from path coefficient analysis showed that seed weight had direct positive effect on yield in all locations. The direct positive effect of seed per pod was negated by indirect effect tiller number in two out of three locations and all locations combined.

Productive tiller number

The results from Pearson correlation coefficient analysis showed that seed yield had the positive correlation with tiller number in all locations (College Station ($r=0.72$, $p<0.01$), McGregor ($r=0.88$, $p<0.01$), and Yoakum ($r=0.67$, $p<0.05$)), including all locations combined ($r=0.87$, $p<0.01$) (Table 4.2). Tiller number had negative correlation with pods per tiller in all locations (College Station ($r=-0.85$, $p<0.01$), McGregor ($r=-0.75$, $p<0.01$), and locations combined ($r=-0.88$, $p<0.05$)), except Yoakum.

The results from path coefficient analysis showed that tiller number had direct positive effect on yield in all locations. However, the direct positive effect of tiller number was large and not affected by other component traits, resulted in highly positive correlations on seed yield.

In Summary, all the locations (College Station, McGregor, and combined) except Yoakum, showed a consistent pattern of results (Table 4.2). Yield was positively correlated with tiller number ($p<0.01$) and seed per pod ($p>0.05$) and negatively correlated with pods per tiller

($p<0.01$) and seed weight ($p>0.05$). However, the effect of seed weight and seed per pod on yield was not significant at 0.05 probability level. The strong positive correlation between the tiller number and yield suggested that tiller number was the most contributing factor to flax yield. The effect of tiller number was almost equally negated by the pods per tiller (Table 4.3) except at McGregor. With the limited supply of inputs, increasing the tiller number results in the decreasing number of pods per tiller as supported by the negative correlations between tiller number and pods per tiller. Thus, the simultaneous selection for both tiller number and pods per tiller in the same direction would be difficult. The negative correlation of pods per tiller agreed with the synonymous parameter of pods per unit area in the paper by Albrechtsen and Dybing (1973). The number of seed per pod, in contrary to the results of Albrechtsen and Dybing (1973), was positively correlated with the yield. However, the research results from different studies indicated that the effect of different components on the yield largely varied depending on the environment, management, and the type of yield components considered for the assessment of yield (Heinrich, 1983; Giunta, 1993; Tivoli, 1996). In this study, seed per pod had a in-significant effect on the yield. Seed per pod and pods per tiller were negatively correlated with each other, but not significant ($p>0.05$).

Yoakum had totally different effects of components on yield compared to the other two locations and the combined analysis. However, Yoakum had only one year data, 2010-2011. Pods per tiller, seed weight, and tiller number had positive correlations with yield. Tiller number was the major positive contributor of the yield ($p<0.01$), consistent with the other two locations and combined. Seed weight, contrary to the other locations, was positively correlated with the yield, similar to the results (synonymous parameter 1000 seed weight) of Rahimi et al. (2011). Seed per pod was negatively correlated with seed yield at Yoakum, which confirmed the results of Albrechtsen and Dybing (1973).

At all locations, tiller number had highest positive direct effect on total seed yield. This direct effect was negated by pods per tiller and seed weight at College Station and locations combined. At McGregor, surprisingly, the indirect effect of pods per tiller was

complementary to the direct effect of tiller number for total yield and vice versa. The direct positive effect of pods per tiller on the yield had compensatory negative effect of tiller number at all locations except McGregor. Likewise, the direct effect of seed per pod on seed yield was negated by the indirect effect of seed weight in two of three locations and vice versa.

4.3.2. Biplot analysis

4.3.2.1.College Station

The biplot analysis of different yield components and overall seed yield of flax at College Station is shown in Fig. 4.1. The results of Pearson coefficient analysis agreed with the results of biplot analysis in College Station. The priciple component 1(PC1) and principle component 2 (PC2) together explained 84% of total variation. An acute angle (< 90 degree) in the figure represents the strong postive correlation and an obtuse angle (> 90 degree) indicates the strong negative correlation (Yan and Tinker, 2006). Number of productive tillers had highest postive effect on the seed yield confirming the results from Pearson correlations. Number of seeds per pod (capsule) had little positive effect on the seed yield of flax. Seed weight and pods per tiller were negatively correlated with seed yield. The tiller number and seed number per pod were positively correlated with eachother. Productive tiller number was the most important contributing factor for overall seed yield of flax.

4.3.2.2. McGregor

The biplot analysis of different yield components and overall seed yield of flax at Mcgregor is shown in Fig. 4.2. The results at McGregor were similar to the results of College Station except the degree of positive correlation between the seed weight and pod number. The results of pearson coefficient analysis agreed with the results of biplot analysis in McGregor. PC1 and PC2 explained 90% of total variance.

4.3.2.3. Yoakum

The biplot analysis of different yield components and overall seed yield of flax at Yoakum is shown in Fig. 4.3. The results of Pearson coefficient analysis agreed with the results of biplot analysis in Yoakum. PC1 and PC2 explained 77% of total variance. Seed yield at Yoakum had significant positive effects of tiller number, pod number per tiller, and seed weight. Seed weight and seed number per pod showed lower discriminating ability at this location. Number of seeds per pod had negative effect on the overall seed yield. The seed number per pod showed positive correlations with tiller number and seed weight and negatively correlated with pod number per tiller. The overall association of yield components and seed yield in this location varied largely from College Station and McGregor.

4.3.2.4. College Station, McGregor, and Yoakum (Combined)

The biplot analysis of different yield components and overall seed yield of flax at combined locations is shown in Fig. 4.4. The results of Pearson coefficient analysis agreed with the results of biplot analysis in locations combined. PC1 and PC2 explained 95% of total variance. Tiller number and seed per pod (capsule) had positive correlations with the seed yield of flax. Tiller number had highest postive effect on seed yield as supported by Pearson coefficient analysis . The seed weight and pods per tiller were negatively correlated with seed yield and also had negative indirect effects on tiller number and seed number per pod. Tiller number and seed per pod were positively correlated with eachother.

In summary, the results from the biplot analysis were similar to the results of Pearson coefficient analysis. Tiller number was the most important contributing factor to overall seed yield of flax. The combined analysis for all three locations were consistent with the College Station and McGregor yield component analysis in both biplot and Pearson coefficient methods. Abundant moisture conditions during the growing season, nutrient status of the soil, and effective control of various biotic stresses (weeds, pests, and

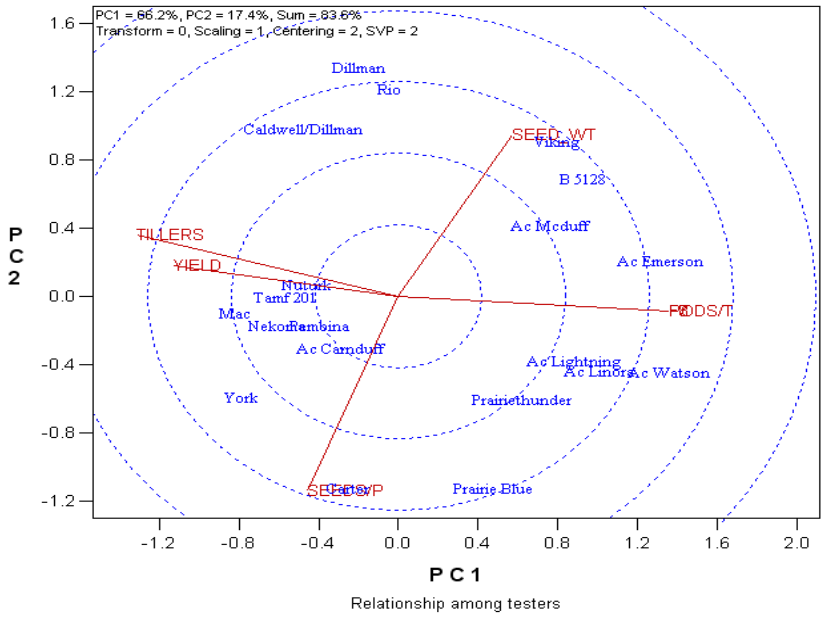

Fig.4.1. Biplot analysis of yield components at College Station, Texas during 2009-2011. PC=Principle Component; SEED_WT= Seed Weight; PODS/T= Pods per tiller; SEEDS/P=Seeds per pod; Ac=AC; Tamf 201= TAMF 201.

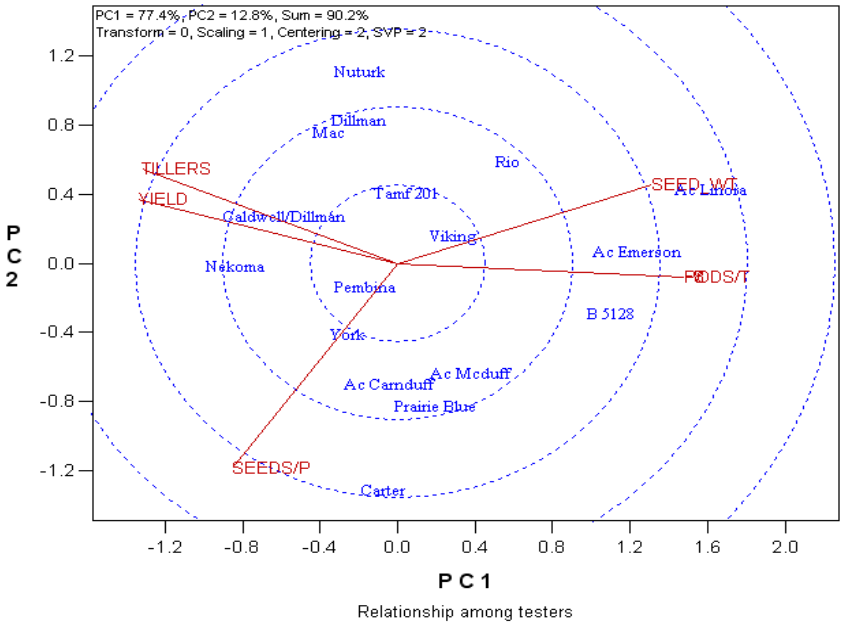

Fig. 4.2. Biplot analysis of yield components at McGregor, Texas during 2009-2011. PC=Principle Component; SEED_WT= Seed Weight; PODS/T= Pods per tiller; SEEDS/P=Seeds per pod; Ac=AC; Tamf 201= TAMF 201.

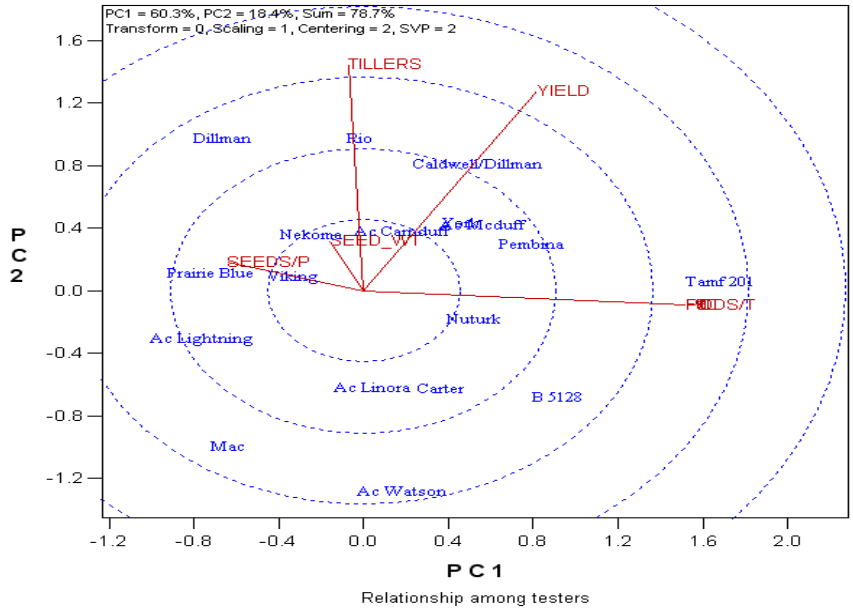

Fig 4.3. Biplot analysis of yield components at Yoakum, Texas during 2010-2011. PC=Principle Component; SEED_WT= Seed Weight; PODS/T= Pods per tiller; SEEDS/P=Seeds per pod; Ac=AC; Tamf 201= TAMF 201.

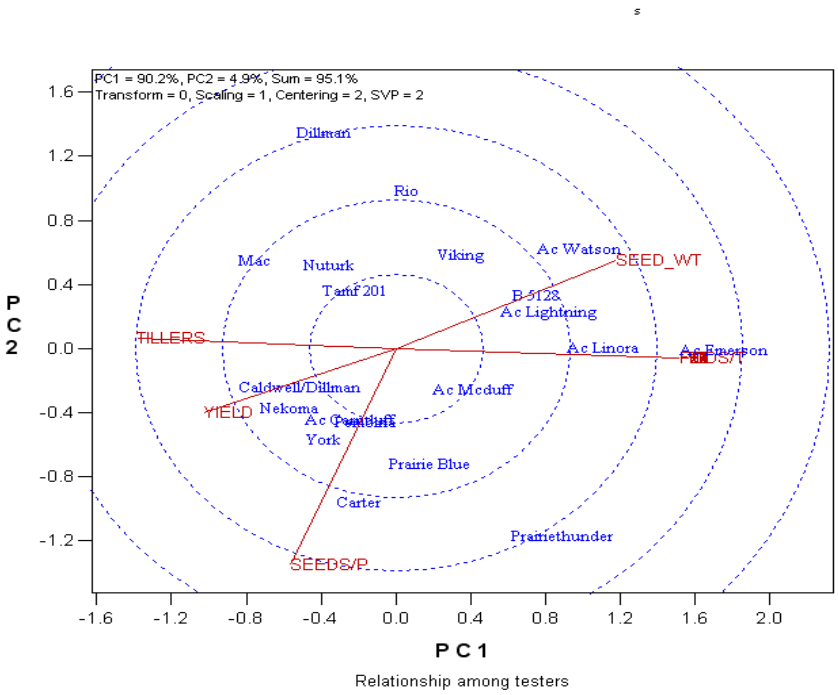

Fig. 4.4. Biplot analysis of yield components at College Station, McGregor, and Yoakum (Combined) during 2009-2011. PC=Principle Component; SEED_WT= Seed Weight; PODS/T= Pods per tiller; SEEDS/P=Seeds per pod; Ac=AC; Tamf 201= TAMF 201.

diseases) would improve the productive tillers contributing to the overall yield of flax. The Yoakum location varied largely from College Station and McGregor. This difference occurred because of different soil and weather conditions. Tiller number is the most beneficial trait to select for increasing the overall seed yield of flax, as its total correlation was positive and significant for yield in all locations. Even though there were consistent compensatory effects in environments; the effects were not large enough to completely offset the positive effect of tiller number on the yield. It was common from the experiment that tiller number and pods per tiller were negatively correlated with each other.

4.4. Conclusions

The results suggest that tiller number was the most significant positive ($p<0.05$) contributing factor for the yields of flax in all three locations. The major finding in this study was that selection for increased tiller number is the best method for increasing flax yield in south east Texas. The strongest correlation between tiller number and seed yield in combined analysis ($r=0.87^{**}$) was similar to the correlation coefficient number ($r=0.85^{**}$) of Rahimi et al. (2011). However, in contrary to Rahimi et al. (2011), the other components investigated in the study like number pods per tiller and seed weight were negatively correlated with the seed yield. The effect of tiller number was almost equally negated by the effect of pods per tiller (compensatory) in two out of three locations and in combined analysis. Whereas Rahimi et al. (2011) reported positive correlation between tiller number and the number of pods. However, it is assume that the mutual compensatory effect existed between the tiller number and number of pods per tiller, depending on the supply of soil moisture . In other words, as the number of tillers increased, the number of pods per tiller decreased and vice-versa. The compensatory effect between tiller number and pod number in relation to low stand densities was also reported in many studies (Diepenbrock and Iwersen,1989; Albrechtsen and Dybing, 1973). Albrechtsen and Dybing (1973) also reported that decreasing the stand densities to 100-700 plants m^{-2} did not affect the seed yield due to increasing the number of pods per plant. The compensatory effect was also true between the seed per pod and seed weight in College Station, McGregor, and the combined analysis. In

these locations, a negative correlation was observed between the number of seed per pod and seed weight. Similar results of negative correlations between seed per pod and seed weight were also observed in Albrechtsen and Dybing (1973). The positive direct effect of tiller number on seed yield was prominent in all locations of southeast Texas, which was also supported by Rahimi et al. (2011). The large direct effect of pods per tiller and seed per pod on seed yield in College Station demonstrated similar results to the research by Vijayakumar and Rao (1975) and Nie et al. (1995). The seed per pod and seed weight were not significant ($p<0.05$) in estimation of yields in flax in Southeast Texas. The Yoakum location showed a different pattern of association between different yield components and yield except tiller number compared to College Station, McGregor, and locations combined. However, the association of yields and its components in flax is site-specific and largely depends on the environment (Heinrich, 1983).

Based on the results, the tiller number provides the most useful trait in the indirect selection for flax breeding program to improve the flax yield in southeast Texas.

CHAPTER V

EFFECT OF VERNALIZATION AND PHOTOPERIOD ON FLOWERING TIMING OF DIFFERENT FLAX GENOTYPES

5.1. Introduction

The adaptation and performance of genotypes for a specific environment depend on the efficiency of selection for a set of desired traits (Annicchiarico, 2002; Eeuwijk et al., 2005). Understanding the environmental factors and their influence on the growth and development of genotypes is essential to identify the physiological, genetic, molecular, and biochemical pathways pertinent for a particular growing climate. The environmental interactions among different genotypes also create an opportunity for breeders to accurately classify genotypes under different adaptive regions. For example, the accurate classification of winter and spring grown flax based on their environmental adaptation influence agronomic management practices (planting date, application of fertilizers, and avoidance of biotic and abiotic stresses) to maximize yield and quality.

5.1.1. Vernalization and photoperiodism

Vernalization and photoperiodism are two important physiological processes that guide the plant responses to the environment (Brutch et al., 2008). The phenomenon of vernalization was first described in the middle of 19th century (Whyte, 1948). Wellensiek (1952) illustrated that the plants require cold temperatures when they reached to certain vegetative periods for effective flowering, and he also demonstrated that plants react to seed vernalization to produce flowering. The research conducted by Sachet (1953) revealed that some determinant plants like wheat require cold temperatures for flowering. He classified flax under the class in which plants require no vernalization for flowering. Chouard (1960) defined the vernalization as "the acquisition or accumulation of the ability to flower by chilling temperature". However, in contrast to the concept of essential requirement of vernalization, Martin (1994) and McKinney (1940) demonstrated some requirement of

vernalization in flax. Chakravarthi (1954) found the inhibitory effects of several auxins upon vernalization of flax. The experiment conducted by Burn et al. (1993) indicated that promotion of flowering occurred through DNA methylation by exposing the plants to prolonged cold temperatures.

Garner and Allard (1920) classified the plants in to long day, short day, and intermediate based on the duration of light requirement for flowering. Nuttonson (1948) classified the flax as a long day plant. Hillman (1967) demonstrated that conversion of Pr (650nm-680nm) to Pfr (710nm-740nm) by exposing the plants to red light trigger the photoperiodic response in the most of the plants but did not test flax. Zeevart (1976) reported a photoperiod response of the plants to cause flowering was initiated by the existence of common floral stimulus referred as florigen. Cajlachjan (1936) indicated that the perception of light occurred in the leaves to convert the vegetative primordia into floral primordia. Hamner and Bonner (1938) demonstrated that 12 hours of continuous light was required for long day plants to flower and the effect was completely erased even with the moon light for the period of 30 minutes. The data from Lang and Melchers (1943) indicated that the temperature intensity has profound influence on the photoperiodic activity of plants. Afonin (1969) indicated that short photoperiods slow down the plant transition to flowering in flax. Apart from the major light factors, application of external growth regulators (auxins) and organic acid induced the flowering in long day plants (Leopald and Thimann, 1949; Klein and Leopald, 1953).

Sizov (1955) reported that flax has no distinct forms of winter and spring type. However, many scientists classified the flax as winter and spring types based on the criterion of planting dates in their region. Sinskaya (1951) demonstrated that winter flax genotypes undergo dormancy during freezing temperatures in order to protect their reproductive organs. An experiment conducted by Brutch et al. (2008) reported that winter type flax did not necessarily (not obligatory) require low temperatures for flowering but they also indicated that under long-day conditions, exposing the seedlings to low temperatures speed

up the flowering. They also indicated several early and late maturity genotypes were insensitive to 12 hour photoperiod experiments.

5.1.2. Indeterminate flowering of flax in Texas

Flax is grown in the U.S. under both spring and winter situations depending on the climate and the region of adaptation. The flax is grown as a winter crop under the Texas conditions (southern latitude). The flax research in Texas from 1930's to 1970's suggested that the cropping period under winter conditions ranges from mid- November to May (typically 6 months) (Hodges et al., 1970). The flax is grown as a spring crop in northern latitude regions (North Dakota and Minnesota) in U.S. The planting season in these regions ranges from April to August (4 months) (Berglund and Zollinger, 2007). The peak flowering period for winter planting usually extended from mid-February to end of March (30-45 days) for different genotypes (winter and spring genotypes) compared to 15-25 days flowering period in the spring planting (Flax Council of Canada). The prolonged cooler temperatures under field conditions seem to contribute to the tiller development throughout growing season, which extend the flowering period of the winter planting.

Although the physiological impact of vernalization and photoperiodism on flowering is well established and understood in many cereal crops (Midmore et al., 1982; Mossad et al., 1994), the importance of the vernalization and photoperiodism in the flax is not well known. Identification of the vernalization and photoperiodic requirements of different genotypes through controlled situations, will allow for the categorization of genotypes and the implications to the field situations for the better management decisions to maximize the yields.

The main objective of the study was to evaluate the effect of vernalization and photoperiod on the anthesis of different genotypes of flax. Also, to determine the genotypes developed in Texas were truely 'winter type'genotypes. The implication of existence of 'winter type' genotypes and their selection for winter environments would help in achieving higher flax yields in the southern latitude crop production regions.

5.2. Materials and methods

5.2.1. Experimental design and treatments

The 20 genotypes were exposed to two vernalization regimes (vernalized and unvernalized) and two photoperiodic durations (10 and 14 hours) (Table 5.1). Each treatment was replicated three times in a split-split plot design with a main factor being two photoperiods, sub-factor being two vernalization regimes, and sub-sub factor being 20 flax genotypes. A 15 x 15 cm size pot was used an experimental unit and equal number of pots were split between two growth chambers with 120 pots in each.

The statistical analysis was conducted using SAS software (SAS, 2008). Analysis of variance (ANOVA) for various factors and their interactions was created using PROC GLM procedure. The pots were arranged in a complete randomized design within each growth chamber due to uniformity of experimental conditions. The data was analyzed in a split-split factorial design with the genotype as a highest precision factor (sub-sub factor). The mean separation test was conducted among different genotypes exposed to vernalization and photoperiodic treatments by using Duncan's multiple range test at 5% significance level.

5.2.2. Methodology

Forty round petridishes with the dimensions of 15 wide X 2 cm depth were used for the two vernalization treatments. A blotting tissue paper with two layers was arranged at the bottom of each petridish and thoroughly watered. Approximately 150 seed for each of the 20 varieties was placed in two petridishes. One petridish was incubated at 3°C for 10 days and the second petridish was maintained at room temperature (approximately 25°C). The petridishes were watered every 48 hours to maintain the constant moisture conditions for uniform germination of the seed. To avoid seed-borne pathogens on the seeds, fungicide (N-Trichloromethylthio-4-cyclohexene-1,2-dicarboximide @ 0.5gram per liter) was mixed with water and applied to the blotting paper for both vernalized and unvernalized petridishes.

Table 5.1. Flax genotypes evaluated for vernalization and photoperiodism in a growth chamber study in College Station, TX.

Genotype	Developer	Release date
AC Carnduff	AAFC[a]	1996
AC Emerson	AAFC	1994
AC Lightning	AAFC	2001
AC Linora	AAFC	1991
AC McDuff	AAFC	1993
AC Watson	AAFC	1995
Prairie Thunder	AAFC	2006
Prairie Blue	AAFC	2006
Carter	NDSURF[b]	2004
Nekoma	NDSURF	2002
Pembina	NDSURF	1999
York	NDSURF	2002
Caldwell/Dillman	TAES[c]	1961
Dillman	TAES	1965
Mac	TAES	1967
TAMF 201	TAES	1960
Nuturk	Unknown	Unknown
B 5128	NDSU[d]	1943
Rio	Unknown	Unknown
Viking	NDSU	Unknown

[a]Agriculture and Agri Food Canada
[b]North Dakota State University Research Foundation
[c]Texas Agricultural Experiment Station
[d]North Dakota State University

Round pots with the dimensions of 15 X 15 cm were filled with planting material up to 3/4 full.Before filling the pots with planting material, fertilizer was applied in the proportion equaling to 34 kg ha^{-1} of nitrogen, 17 kg ha^{-1} of phosphorous, and 17 kg ha^{-1} of potash. Allthe pots were watered thourghly before planting to avoid drifting of the seed. The vernalized or unvernalized seedlings of each genotype were transplanted at a cotyledon stage from petridishes to pots for a total of 6 pots (2 photoperiodic treatments X 3 replications). Twenty seeds of each vernalized or unvernalized seed were planted in each pot at a depth of 1.25 cm and transferred to greenhouse. Each pot was labeled representing vernalization regime, photoperiodic treatment, and replication number. After the plants reached about 5 cm height, the pots were transferred from the greenhouse to two growth chambers with 10 hours and 14 hours of light while temperature and humidity were held constant. The day and night (diurnal) temperatures were maintained at 22 and 16°C, respectively. However, during the plant growth, the growth chamber of 14 hours photoperiodic treatment recorded consistently lower temperatures due to non-working nature of humidity controls. So, the temperatures were recorded two times a day, representing day and night time temperatures around 2 pm and 9 pm respectively. The temperatures were adjusted manually in the growth chamber, matching 22 and 16^{o}C for day and night temperatures, respectively.

Hundred and twenty pots (20 genotypes X 2 vernalization regimes X 3 replications) pots were arranged in a completely randomized design for each of the two photoperiodic treatments. The pots were watered to maintain the proper moisture conditions for plant growth. The pots were thinned to 5 plants pot^{-1} after stand establishment. At the peak vegetative growth, a liquid fertilizer equaling to 34 kg/ha of nitrogen, 17 kg/ha of phosphorous, and 17 kg/ha of potash were applied to the soil.

For each genotype the first flowering date was recorded for pot. The first flowering date was defined as the date on which approximately 50% of plants were in bloom. Intrinsic earliness, basal vegetative period (BVP), of a genotype was measured as time required for vernalized seedlings to reach anthesis stage in the longest photoperiod (14 hours) (Midmore

et al., 1982; Pernose et al., 1991; and Mosaad et al., 1994).). The genotypes were classified as “sensitive to vernalization” if unvernalized seedlings delayed the anthesis by 7 or more days under 14 hours daylength conditions. Likewise, the genotypes were classified as “sensitive to photoperiod” if vernalized seedlings delayed the anthesis by 12 or more days under short day length (10 hours) conditions.

5.3. Results and discussion

The ANOVA conducted for various main and interaction effects of photoperiod and vernalization on flowering period identified differences among two photoperiods ($p<0.01$), two vernalization treatments ($p<0.01$), and genotypes ($p<0.001$) (Table 5.2). The interactions between genotype and photoperiod ($p<0.001$) and genotype and vernalization ($p<0.05$) were also significant, which indicated the difference in the response of various tested genotypes when exposed to different vernalization and photoperiodic treatments. However, there was no interaction between the photoperiod and vernalization ($p<0.05$), meaning two physiological processes acted independently of each other in flowering response of flax. The genotypes were classified into different response groups for vernalization and photoperiod based on BVP (Table 5.3). The BVP varied largely across the genotypes and ranged from 38.7 to 77.3 days. Southern latitude genotypes (Caldwell/Dillman, Mac, Dillman, and TAMF 201) showed higher BVP compared to most of the Northern latitude genotypes ($p<0.05$). The Southern latitude genotypes were all sensitive to both vernalization and long photoperiods compared to non-vernalized and short photoperiods for anthesis ($p<0.05$). Southern latitude genotypes delayed the anthesis for 7 days or more in unvernalized seedlings, whereas most of the other genotypes showed no difference between vernalization and unvernalization treatments except Prairie Thunder. Prairie Thunder seemed to respond to vernalization. The pedigree of Prairie Thunder is FP974/FP1043 (FP974=AC Watson x AC Emerson/AC Linora). All parents in the female pedigree were insensitive to vernalization. The pedigree of male parent ‘FP1043’ was unknown. However, it is possible that the genes from male parent could cause sensitivity of

Table 5.2. Analysis of variance of main effects of photoperiod, vernalization, genotypes, and their interactions for days to anthesis under growth chamber conditions.

Source of Variation	Degrees of Freedom	Mean Square	F- Value[a]
Replication	2	171.3	1.7 NS
Photoperiod (P)	1	6869.4	68.32**
Error	2	100.5	
Vernalization (V)	1	904.8	40.1**
P*V	1	88.8	3.9NS
Error	4	22.6	
Genotype (G)	19	2945.6	126.8***
G*P	19	171.2	7.4***
G*V	19	40.3	1.7*
G*P*V	19	11.4	0.5 NS
Error	152	23.2	
Total	239		

[a]F-value * P≤ 0.05
** P≤ 0.01
*** P≤ 0.001
NS- Not Significant at 0.05 probability level

Table 5.3. Basal vegetative period (BVP), mean effect of vernalization (ΔV), and mean effect of daylength (ΔP) for 20 genotypes of flax tested under growth chamber conditions.

Genotype	BVP	ΔV[a]	ΔP[b]
Nuturk	77.3 a	3.0 (-) de	19.7 (+) ab
Mac	75.7 ab	8.0 (+) ab	14.3 (+) c
Dillman	74.7 ab	7.6 (+) ab	19.4 (+) ab
Caldwell/Dillman	74.0 ab	9.7 (+)[c] a	23.0 (+) a
B5128	74.0 ab	0 (-) e	8.0 (-) ef
TAMF201	73.3 b	8.3 (+) ab	13.4 (+) cd
Nekoma	71.6 bc	-4.3 (-) d	1.0 (-) h
Rio	71.3 bc	5.7 (-) cd	3.7(-) gh
AC Lightning	68.3 bc	6.0 (-) c	2.4 (-) gh
Viking	64.7 c	0 (-) e	12.7 (+) d
Prairie Blue	64.6 c	1.0 (-) e	4.0 (-) fgh
York	63.7 cd	-1.0 (-) e	9.7 (-) def
AC Carnduff	63.3 cd	-1.0 (-) e	3.3 (-) gh
AC McDuff	63.3 cd	0 (-) e	11.0 (-) de
Prairie Thunder	62.3 d	7.3 (+) b	5.0 (-) fgh
AC Emerson	51.6 e	0 (-) e	-0.7 (-) h
AC Linora	42.6 fg	0 (-) e	11.4 (-) de
Pembina	41.6 fg	0 (-)[d] e	7.4 (-) fg
AC Watson	39.0 g	0 (-) e	8.0 (-) ef
Carter	38.7 g	4.0 (-) d	8.4 (-) ef

[a]ΔV - Response to vernalization
[b]ΔP - Response to photoperiod
[c](+) = sensitive
[d] (-) = insensitive
Mean separation test was conducted by using Duncan's multiple range test at 0.05 significance level

Prairie Thunder to vernalization temperatures. Southern latitude genotypes also delayed the anthesis for 12 days or more in short day conditions compared to long day conditions under vernalized conditions, whereas other genotypes showed no difference between the short day and long day conditions in vernalized seedlings except Nuturk and Viking ($p<0.05$). Nuturk and Viking were the historical genotypes that showed significant early response in the anthesisperiod for long day conditions. The requirement of long day photoperiod for vernalized seedlings to hasten the flowering was also supported by Brutch et al. (2008). However, there was no indication of non-flowering observed in either winter or spring type flax genotypes in the absence of vernalization and long photoperiod. This finding was also similar to the reports by Brutch et al. (2008). In other words, the only difference between Northern latitude genotypes and Southern latitude genotypes of flax, in the view of vernalization and photoperiodism, was early response of flowering in Southern latitude genotypes. The short photoperiods did not inhibit the flowering totally, but delayed the flowering, which agrees with findings by Afonin (1969). Being bred and adapted in the cold environment, Southern latitude genotypes (winter type) undergo dormancy in the months of January and February inorder to protect their reproductive organs (Sinskaya,1951) which attributes to survival mechanism from cold temperatures. After prolonged cold temperatures, onset of normal temperatures in the periods of late February and March induces flowering. The Northern latitude genotypes (North Dakota and Canadian genotypes), developed for spring planting, earliness in flowering was not influenced by vernalization or long day conditions for anthesis.

5.4. Conclusions

Genotype differences were observed for both vernalization and photoperiod. The Southern latitude genotypes were sensitive to both vernalization and photoperiods for flowering. One possible reason for the sensitiveness of all Southern latitude genotypes (Texas genotypes) to vernalization could be the common parental genes of Roman Winter (a Holland variety) that attribute to vernalization response. Southern latitude genotypes delayed the anthesis for 7 days or more in unvernalized seedlings, whereas most of the other genotypes showed no

difference between vernalization and unvernalization treatments. Both Northern and Southern latitude genotypes flowered eventually in either presence or absence of vernalization. The essential nature of vernalization for flowering of flax was not supported in the current research, meaning both North and South latitude genotypes flowered even in absence of vernalization temperatures. It was also evident from the results that vernalization speed up the flowering in Southern latitude genotypes under long day conditions (Brutch et al, 2008); while Northern latitude genotypes showed no influence of vernalization on the anthesis period. The non-essential nature of vernalization for flowering in flax was also supported by Sachet (1953). Southern latitude genotypes also delayed the anthesis for 12 days or more in vernalized and short day conditions, whereas Northern genotypes showed no difference between the short day and long day conditions in vernalized seedlings. Brutch et al. (2008) reported that early and late maturing genotypes of flax were insensitive to 12 hours of photoperiod. The current results demonstrated that exposing the Southern genotypes to 14 hours of daylight under growth chamber conditions resulted in early anthesis. Based on the results, the Texas genotypes (Southern latitude) showed significant response to the vernalization and photosensitivity compared to spring type (Northern latitude). Meaning, winter and spring type genotypes differ in degree of response for vernalization and photoperiod. However, the vernalization and photosensitivity are not the essential requirements of flowering for both winter and spring type genotypes. The classification of flax genotypes into winter and spring type only based on the vernalization and photosensitivity requirement is not appropriate as both types flower irrespective of their requirements. However, it would be more plausible to classify the flax genotypes into spring and winter types based on the planting dates (Sizov, 1955) and their relative cold tolerance. The selection and breeding for winter genotypes based on the cold tolerance in coupled with earliness of flowering would help in achieving better yields in Texas.

CHAPTER VI

CONCLUSIONS

The spring rapeseed was a potential biofuel crop for subtropical subhumid and subtropical humid environments of Southern Texas, specifically the central and south Texas regions. The exception was under the highest annual precipitation in Southeast Texas, Beaumont. In each of these trials, the spring rapeseed was fall planted and outperformed the winter rapeseed. Poor performance by the winter rapeseed was partially due of inadequate cold temperatures to vernalize the rapeseed and reduced reproductive development. Spring rapeseed yielded high in locations at Beeville and at lower latitude locations compared to other three cool-season oil-seed crops. Safflower generally yielded slightly lower than the spring rapeseed for seed yield in Beeville and the southern locations; however, the overall oil yield is substantially lower for safflower because of the low oil content of the seed. Flax had the highest seed and oil yield in the southern subtropical humid region of the state, including College Station and Beaumont.

In the northern locations of the study, in the subtropical humid, subtropical subhumid, and cool temperate zone locations, the stand establishment and winterkill dramatically influenced the ability to quantify the yield potential of all the cool-season oil-seed crops. Much of the stand establishment problems were associated with the dry soil and limited precipitation at the time of planting and the inability to plant the small seeded crops at a sufficient depth for the seed to have adequate soil moisture to initiate germination. Additionally, the precipitation distribution in non-irrigated fields makes crop establishment a challenge in the Rolling Plains and High Plains of Texas. This is a challenge for the current winter crops, such as wheat, but, delayed emergence of wheat does not substantially increase its susceptibility to winter kill in these regions. However, delayed emergence with the cool-season oil-seed crops can cause complete winter kill. Last, high temperature stress at critical reproductive stages was detrimental to the yield and adaptation of tested cool-season oilseed crops in the High Plains of Texas.

Safflower was the most consistent yielding crop and this was in part due to the larger seed size and ability to plant the seed at a deeper depth and consistently obtain a stand. Grain yields of safflower exceeded 1000 kg ha^{-1} at all the locations and were over 2000 kg ha^{-1} at Prosper. Despite the adaptability, good agronomic characteristics, and consistency in grain yields, the oil production per ha from safflower was not consistently greater than the other oil-seed crops.

The twenty flax genotypes tested in College Station, McGregor, and Yoakum during 2008-2011 differed considerably due to broader genetic and environmental factors. In all flax tested locations, the climate is broadly classified as subtropical humid conditions. Even though the tested locations of flax were not vastly different from each other in terms of latitude, annual precipitation, and annual temperature, the weather and soil conditions during critical stages of crop growth and development impacted the yield and adaptation of different genotypes of flax. All genotypes showed significant interaction with the environment. The genotypes adapted for May-planting of North Dakota and Canada (Northern latitude genotypes) showed higher yields in a non-cold 2008-2009 year of College Station compared to Texas (Southern latitude) genotypes. The yield improvement could be attributed to the genetic improvement of flax from 1970 to current date due to the introduction of advanced lines and breeding. However, it was clear from the 2010-2011, cold-year both in College Station and McGregor, that southern latitude genotypes showed considerable cold tolerance and yield advantage over north latitude genotypes due to the selection advantage of Texas genotypes in cold environment. Moreover, it is believed that Roman Winter, a common parent in all Texas genotypes, is the source that imparts cold tolerance to all Texas genotypes. The Caldwell/Dillman cross showed consistent level of adaptation among all genotypes during the tested years in the mega environment, representing College Station and McGregor. The mean yield of flax was highest in College Station with a three-year average of 1345 kg $ha^{-1}$and average oil content of about 40%. Historically, the flax acreage was mostly concentrated north of Corpus Christi, Texas during 1930-1970, where subtropical humid climate was predominant. The adaptation of flax to the subtropical humid climate of Texas is similar to the climatic pattern of Mediterranean center

of diversity. Most of the acreage in Texas was limited to marginal and non-irrigated lands, where low input production was common. In addition to the low input production, the most yield limiting factor for fall planted flax was cold susceptibility, especially as the flax production moved toward Central Texas. The flax breeding efforts during 1960-1970 released prominent cold-tolerant genotypes, which helped Texas flax production at that time. The confirmation of cold tolerance of southern genotypes was observed in the cold-years of College Station and McGregor trials. In Yoakum, being the most southern location, the cold injury was not an issue during the 2 years of the trial. However, the stand establishment and high soil salinity were the major issues of flax production at this location. Selection of the cold tolerance trait from Texas genotypes and introgression into modern high yielding genotypes should provide a significant advancement in flax development in southeast Texas.

The productive tiller number was the most positive significant ($p<0.05$) contributing factor for the yield of flax in all three locations of southeast Texas. It was also evident from other major crops like sorghum and corn that the tiller number contributes significantly to the seed yield. However, the relative contribution of tiller number to the yield is highly environment dependent and balance out the plant carbon with the availability of assimilates (Mitchell, 1953; Ong and Marshall, 1979). In other words, the tiller emergence is mostly influenced by available moisture and fertility conditions. The effect of tiller number on seed yield of flax was highest in College Station compared to other locations due to better soil moisture conditions. It was also observed that during high cold stress conditions, the low plant density was compensated by the profuse tillering habit of southern genotypes, resulting in higher yields. All northern latitude genotypes were erect growing with less number of tillers. With the limited inputs, the tiller number had a compensatory effect on pods per tiller, as they were negatively correlated to each other. The similar kind of compensatory effect was also observed in seed per pod and seed weight. The seed per pod and seed weight were not significant ($p>0.05$) in estimation of yields in flax. Based on the results, the tiller number provides the most useful trait in the indirect selection for flax breeding program to improve the yields of southeast Texas.

Southern latitude genotypes (fall-planted) were sensitive to both vernalization and photoperiods for flowering. The likely reason for sensitivity of all Texas genotypes to vernalization could be the presence of vernalization response genes in Roman Winter genotype, a common parent to all Texas genotypes. Southern latitude genotypes delayed anthesis for 7 daysto 10 days in unvernalized seedlings, whereas most of the other northern genotypes showed no difference between vernalized and unvernalized treatments. In general, the response of southern latitude genotypes to the vernalization should result in early maturation due to early flowering. Contrary to this belief, it was observed from field experiments that the profuse tillering at various stages of plant growth of these genotypes delayed the overall maturation period. However, if the cold temperatures occur at both early and mature stages of plant growth, cold injury at mature stage cause more yield loss due to lack of rejuvenation of productive tillers at later stages of plant growth. Unlike winter wheat, flax does not require vernalization for flowering. Typically, under North Dakota conditions, May-planting of flax hardly receives any vernalization for seedlings. However, the lack of vernalization temperatures does not inhibit the flowering of flax under North Dakota conditions. In other words, flax did not require vernalization for flowering of northern latitude genotypes. In Southern latitude genotypes, exposing the seedlings to vernalization temperatures sped up the flowering process significantly. The possible reason might be related to the occurrence of vernalization genes in those genotypes, sharing a common parent source. Southern genotypes also delayed anthesis for 12 days or more in vernalized and short day conditions compared to vernalized and long days, whereas northern latitude genotypes showed no difference between the short day and long day conditions in vernalized seedlings. The selection and breeding for winter genotypes based on the cold tolerance coupled with earliness of flowering and higher tiller number would help in achieving better yields in flax in southeast Texas.

All cool-season oilseed crops were evaluated under dryland conditions and recommended management in Texas. The evaluation of all cool-season crops at all locations were aimed to determine the yield potential for biofuel feedstock. Considering the current acreage demand for corn and other traditional food crops like wheat, replacing the core agricultural land with

oilseed crops is often challenging. Moreover, the marketing facilities for those evaluated oilseed crops are currently limited. The decision regarding the balance of acreage for food and fuel is always a challenge for the scientific community.

A severe energy crisis will develop if the fossil fuel supply is exhausted by 2050, as projected by BP review of world energy. Finding alternative energy sources in the coming decades is a necessity. Clearly, there is no single answer for the replacement of fossil fuels, but the evaluation of alternatives to fossil fuels, such as biofuel crops, is important. Apart from existing first generation biofuels, more advanced second-generation biofuels and more efficient enzymatic technology will help the biofuel industry in contributing to future global fuel demand.

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