Agronomic Aspects of Fibre Flax Production in Québec

Scott J. Couture

Department of Plant Science

Macdonald Campus of McGill University

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Abstract

The potential of using fibre flax cultivars developed in Europe for production in Québec and Eastern Ontario was investigated in 1997 and 1998, in field trials at Macdonald Campus, McGill University, Ste. Anne-de-Bellevue, Québec and at Winchester and Kemptville, Ontario. A total of 11 cultivars were evaluated based on parameters pertinent to successful production. The French cultivar 'Ariane' stood out as the cultivar whose performance was most consistent across a variety of soil types and locations. The best method of establishing fibre flax (c.v. Ariane) in terms of seeding depth (zero, one, two, four or six centimeters), with soil compaction prior to vs. after seeding, or not at all, was also investigated during 1997 and 1998 at Macdonald Campus. Results were somewhat contingent on soil type at a specific site, but generally, a shallow seeding depth of one or two centimeters is best, with soil compaction prior to seeding more effective in lighter soils, and the same shallow seeding depth with no soil compaction in heavier soils. Preliminary investigations at Macdonald Campus in 1998 indicate good potential for the production of fibre flax (cv. Ariane) in minimum and zero tillage systems compared with conventional tillage. There were no significant differences between treatments in fresh straw yield, and minimum tillage plots produced significantly taller plants in one of the two sites. Overall, findings from this research indicate that fibre flax can successfully be produced in Eastern Canada using cultivars of European origin and in a variety of tillage systems.

Résumé

La possibilité d'utiliser au Québec et en Ontario, des variétés de lin textile developé en Europe fût investigués dans des essais de champ en 1997 et 1998 au Campus Macdonald de l'Université McGill, Ste. Anne-de-Bellevue, Québec, et aussi à Winchester et Kemptville, Ontario, Canada. Onze variétés fûrent évaluées selon leurs caracteristiques reliées a l'importance de la production au niveau local. La performance de la variétié 'Ariane' fût la plus consistente dans des conditions variés incluant le type de sol et la location géographique. La meilleure methode pour l'éstablissement du lin textile (cv. Ariane) en termes de profondeur (zero, un, deux, quatre, ou six centimetres), en combinaison avec un passage du rouleau avant ou apres semis, ou sans rouleau, fût investigué sur quatre sites au Campus Macdonald en 1997 et 1998. Les résultats dependaient légèrement du type de sol. La profondeur d'un ou deux centimetres était meilleure avec un passage du rouleau avant semis dans les sols légèr. La même profondeur d'un ou deux centimetres sans passage du rouleau était plus éffice dans les sols plus lourds. Une évaluation préliminaire de la production de lin textile dans les systemes à travail minimale ou aucune travail de sol, investigué sur deux sites au Campus Macdonald en 1998, indique un grand potentiel. Les résultats n'indiquent aucune difference de rendement de lin textile entre traitement de systeme de travail de sol. Les plantes les plus hautes fûrent trouvées dans les parcelles à travail minimale sur l'un des deux sites. En conclusion, les résultats indiquent que le lin textile pourrait être cultivé a l'Est de Canada avec des variétes provenant de l'Europe, et a l'interieure de plusieurs systèmes de travail de sol.

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Description of Thesis Format

This thesis has been submitted in the form of original papers suitable for journal publications. Chapter one is a general introduction that includes a literature review that describes the body of knowledge from which this research grew. Chapters two, three and four represent the body of the thesis, and chapters three to five each representing a complete manuscript. Chapter five is a general discussion that includes the major conclusions of each chapter. This format has been approved by the Faculty of Graduate Studies and Research, McGill University, and follows the conditions outlined in the Guidelines Concerning Thesis Preparation, section B part 2 "Manuscript and Authorship" which states the following:

"The candidate has the option, ***subject to the approval of their Department****, of including as part of their thesis, copies of the text of a paper(s) submitted for publication, or the clearly duplicated text of a published paper(s), provided that these copies are bound as an integral part of the thesis.*

If this option is chosen, ***connecting texts, providing logical bridges between the different papers, are mandatory****.*

The thesis must still conform to all other requirements of the "Guidelines Concerning Thesis Preparation" and should be in a literary format. It should be more than a mere collection of manuscripts published or to be published. The thesis must include, as separate chapters or sections: 1) a Table of Contents, 2) a general abstract in both English and French, 3) an introduction which clearly states the rationale and objectives of the thesis, 4) a comprehensive review of the background literature to the subject of the thesis, when this review is appropriate, and 5) a final overall conclusion and/or summary.

Additional material (procedural and design data as well as descriptions of equipment) must be provided where appropriate and sufficient detail (eg. in appendices) to allow a clear and precise judgment to be madeof the importance and originality of the research reported in the thesis.

In the case of manuscripts co-authored by the candidate and others, ***the candidate is required to make an explicit statement in the thesis of who contributed to such work and to what extent****; supervisors* *must attest to the accuracy of such claims at the Ph.D. oral defense. Since the task of the Examiners is made more difficult in these cases, it is in the candidate's interest to make perfectly clear the responsibilities of the different authors of co-authored papers."*

All the work represented herein is the responsibility of the candidate, the project was supervised by Dr. A.K. Watson, and co-supervised by Dr. A. DiTommaso, both of the Department of Plant Science, Macdonald Campus of McGill University. Both co-supervisors reviewed all manuscripts and are co-authors of manuscripts two through four. Miss W. Asbil, Kemptville College, University of Guelph, was responsible for the experimental design of field trials in the growing season of 1997 (chapters two and three). Miss Asbil also reviewed all manuscripts, and is a co-author of manuscripts two through four.

For consistency and convenience, all manuscripts follow the same format. The copies to be sent to the respective journals will follow the format specified by each journal. Manuscript two is to be submitted to the Agronomy Journal. Manuscripts three and four are to be submitted to the Canadian Journal of Plant Science.

Chapter 1. General Introduction

1.1. Abstract

Flax is an ancient crop used historically for both the fibres found in the stem, and the oil found in the seeds. Breeding efforts have enabled cultivars to be developed specifically for fibre production or oil production, although dual-purpose cultivars exist in many Eastern European nations and other developing countries. Fibre flax was once grown widely in Eastern Canada and in the United States but competition from other natural and synthetic fibres led to its disappearance from North America. Oilseed flax is currently widely produced in Western Canada and the Midwestern United States, however fibre flax is primarily produced in Eastern and Western Europe, the former Soviet Union and other Baltic states, and China. Industrial applications of the fibres from flax plants are currently being developed and fibre flax is currently being embraced as a multipurpose crop in many areas of the world.

1.2. Taxonomy and history

Flax (*Linum usitatissimum* L.) is a member of the *Linaceae* family and is native to regions of Asia and the Mediterranean (Berger, 1969; Langer & Hill, 1991). This plant is widely distributed and is an important source of fibre and oil (Marshall et al., 1989; Diederichsen & Hammer, 1995). *Linum usitatissimum* (hereafter referred to as fibre flax) is the only species out of about 150, which has agricultural significance within the family (Langer & Hill, 1991). There are 136 known accessions of *Linum usitatissimum*, of which 73 are wild progenitors (subsp. *angustifolium* (Huds.) Thell.), and 63 are cultivated cultivars (subsp. *usitatissimum*) (Diederichsen & Hammer, 1995).

The fibre derived from the flax plant is known as linen, and was of great importance as long ago as 5000 years, when the ancient Egyptians recorded the processing procedure, called retting, in the form of pictures and art (Berger, 1969; Bishop et al., 1983). The fibre was also used in the embalming procedure of mummies (Marshall et al., 1989; Langer & Hill, 1991). The oil derived from flaxseed is known as linseed oil, and its properties were recognized well before the usefulness of flax fibre was mastered (Berger, 1969; Lee, 1987). The ancient Egyptians also used the oil in the embalming process (Langer & Hill, 1991). Linseed remains today important in the paint and varnish industry, with Canada being one of the major exporters (Hocking et al., 1987).

It is surmised that the Phoenicians were responsible for transporting the plant into Europe, from its possible origin in the Near East (Roseberg, 1996; Stephens, 1997). From there it spread to Russia and Finland. Between 1810-1820, Philippe de Girard acquired a number of patents in France for developing new technology for the spinning of flax fibres (Sultana, 1983; Roseberg, 1996). During the colonial era, European colonists then transported flax to North America, Australia and New Zealand (Roseberg, 1996). Fibre flax prospered in North America for many years as production followed settlers from the east coast westward, until yields began to drop dramatically (Hammond & Miller, 1994). During this time the word spread that fibre flax was hard on the land, taking up substantial amounts of nutrients while doing little to improve soil structure, and returning little back to the soil (Knowles et al., 1959 *in* Hocking et al., 1987). Decades later, researchers agree the likely cause of the decreasing yields was due to disease caused by *Fusarium oxysporum* f. sp. *lini* (Hammond & Miller, 1994).

1.3. Breeding

Fibre flax production decreased worldwide in the early part of this century when other fibres, most notably cotton, were popularized (Ulrich & Laugier, 1995). It was during this time that methods for processing these diverse fibres were perfected. There was an established fibre flax breeding program in the United States from the 1930s to 1950s, but interest declined during the mid 1950s, and flax breeding programs disappeared by the early 1960s (Roseberg, 1996). The reintroduction of fibre flax in Europe following World War II played a significant role in this decline, as well as the introduction of petroleum-based fibres such as nylon (Scholz, 1995; Roseberg, 1996).

A number of trials were conducted in the province of Saskatchewan during the late 1970's to evaluate the potential of growing fibre flax in this region (Rowland, 1980). Fibre flax cultivars had not been evaluated since 1957 in Canada, and never at all in Saskatchewan (Rowland, 1980). Cultivars from Western Europe were evaluated by the Crop Development Centre (CDC), in a number of locations in the province, and results suggested that the fibre cultivars produced significantly more fibre than oilseed cultivars already grown in the region, and yielded only slightly less than those same cultivars in Europe (Rowland, 1980). Ulrich & Laugier (1995) concluded that fibre flax would likely succeed in the area under irrigated conditions.

Historically, flax has been grown for both oil and fibre while recent breeding efforts have resulted in cultivars specifically bred for either oil or fibre production (Fouilloux, 1989; Foster et al., 1997; 1998). Oilseed cultivars may be distinguished as having a shorter, highly branched stature, which allows for greater seed production

(Berger, 1969; Lockhart & Wiseman, 1988). The seeds typically contain 30-45% more oil than in fibre cultivars (Maiti, 1997). Current breeding programs focus on increasing fibre yield per unit area as well as developing cultivars resistant to fungal diseases such as *Fusarium oxysporum* (Fouilloux, 1989). Also a major concern is breeding for the synchronization of fibre and seed maturity, since a significant portion of the flax in Europe is grown for both seed and fibre (Keijzer, 1989; Foster et al., 1997; 1998). The Institute for Crop Production and Plant Breeding in Bonn, West Germany, has been developing such dual-purpose cultivars since 1983 (Kaul et al., 1994). The University of Birmingham, U.K., has also been involved in similar efforts (Foster et al., 1997; 1998). One of the foremost advantages of dual-purpose cultivars has been linked to the conservation of natural resources, by lowering the demand placed on long rotation agro-forestry programs (Kaul et al., 1994). Similar programs are ongoing in India, where efforts are directed at making use of the agro-waste (flax fibres and shives), rather than burning it (Shaikh et al., 1992).

1.4. Plant description

Fibre flax cultivars tend to be tall with few branches, since seed production is of little importance (Janick et al., 1981; FCC, 1996). Fibre flax is an erect growing annual, often found growing one meter or more in height, depending on climatic conditions and length of the growing season (Langer & Hill, 1991; Maiti, 1997). Narrow lanceolate leaves with entire margins number 80-100 per stem, with the lowermost leaves yellowing and senescing as the plant approaches maturity (Berger, 1969). Distance between leaves on the stem is linked to fibre quality, with greater distances being associated with higher quality fibre (Stephens, 1997).

Fibre flax flowers are composed of five sepals and 5 petals, most often white, pink, or blue in colour, and are short lived and self pollinated (Berger, 1969; Hocking et al., 1987). Five stamens are present, and the ovary has five erect styles (Langer & Hill, 1991). Nectaries are present. Cross-pollination by insects is possible, but rarely occurs (Janick et al., 1981; Bishop et al., 1983). The fruit is composed of a small, round capsule, light brown in colour, containing 8-14 individual seeds (Bishop et al., 1983; Sultana, 1983; Hocking et al., 1987). The seeds measure 4-5 mm in length, are oval in shape, flat, and shiny bronze in colour (Langer & Hill, 1991). A sticky substance is produced when the outer epidermis of the testa imbibes water (Langer & Hill, 1991). The flax plant is easily crossed with other members of the genus, owing in part to its diploid chromosome number of 30, occasionally 32 (Langer & Hill, 1991).

The stems of the flax plant are dicotyledonous in nature, with the central pith being surrounded by a ring of vascular bundles (Langer & Hill, 1991). Between the bark and the woody pith can be found 25-30 fibre bundles surrounding the stem (Berger, 1969; Sultana, 1983). Several individual fibres are contained in each bundle, and are joined at the ends by pectins and gums (Lee, 1987). The fibres of the flax plant are found in the phloem of the stem, running almost the entire length of the plant, from the below ground portion of the stem up to the first branch (Stephens, 1997). These fibres can measure from 5 to 70 mm in length and approximately 20 um in diameter (Langer & Hill, 1991). Fibre flax is considered to be of good quality when it contains a minimum of 60% long fibres, generally greater than 40 mm in length (Sultana, 1983). The shorter fibres, or tow fibres, are less valuable, and are often treated as a by-product (Roseberg, 1997). Pectin and some lignin compose the middle lamella of the fibres, however it is cellulose which makes flax fibres strong, yet soft and flexible, both desirable characteristics in the garment industry (Langer & Hill, 1991; Ulrich & Laugier, 1995).

Stem diameter has also been linked to fibre quality (Hocking et al., 1987). Thinner stems may contain slightly less fibre, however they are less coarse, and easier to ret, minimizing losses in quality common to over-retting (Stephens, 1997). However, thicker stems may mean a greater content of fibre cells, leading to higher fibre content (Hocking et al., 1987). Lodging can be a problem associated with thick stems and fertilizer management (Berger, 1969; Easson & Long, 1992).

1.5. Agronomy

1.5.1 Seedbed preparation and seeding rate

It is recommended that as with other crops, fibre flax be grown in rotation in order to minimize the buildup of pests characteristic to flax culture (Sultana, 1983). Stephens (1997) suggests a 5-6 year rotation in Connecticut. Fibre flax should be seeded into a firm seedbed, plowed the previous fall and cultivated in the spring, to a depth of 1.5-2 cm (Berger, 1969; Sultana, 1983; Lockhart & Wiseman, 1988). Medium-heavy soils are best, such as a well-drained loam or clay-loam (Robinson & Cook, 1931; Berger, 1969; Bishop et al., 1983). Row spacing depends on the type of machinery used, however a narrow row spacing of 6 to 10 cm is preferable (Sultana, 1983). Seeding rates (90-120 kg ha^{-1}) are higher for fibre flax than for oilseed flax and are dependent on seed size and percent germination (Langer & Hill, 1991). Seeding rates as high as 140 kg ha $^{-1}$ in Europe have been reported by Fouilloux (1989), and 180 kg ha $^{-1}$ (Easson & Long, 1992), to achieve stand densities of approximately 3000 plants m^2. Lockhart & Wiseman (1988) report optimal seeding rates for fibre flax in the United Kingdom (UK) to be in the area of 125-150 kg ha $^{-1}$ to attain plant densities of 1800 plants m^2. Rowland (1980) reports that average plant heights decreased with increasing seeding rate, but that total amount of straw produced increased. Kozlowski et al. (1995) also report a straw yield increase following an increase in seeding rate. The increase in straw however was not evaluated as being of superior quality. Guleria & Singh (1983) report slightly different results, including a surprisingly low optimal seeding rate of between 60-80 kg ha $^{-1}$, in their studies in India. Presently in Europe, plant densities of approximately 2000 plants per m^2 are desirable (Sultana, 1983; Stephens, 1997).

1.5.2. Fertilization

Fertilizer requirements for fibre flax tend to be low, however since the root system is limited in size, ample nutrients must be concentrated in the soil and easily accessible to the plants (Berger, 1969). High quality fibres are of greater importance than quantity, and quality tends to decline under heavy fertilizer regimes, which tend to yield much higher quantities of flax straw (Berger, 1969). Robinson (1933) suggested a fertilizer regime of 4-16-8 as far back as 1933, which closely approximates a more recent ratio of 1:0.8:2.5 ($N:P_2O_5:K_2O$) cited as acceptable for fibre flax production by Berger (1969).

Nitrogen (N) has a critical impact on fibre content, fibre length, and stem diameter (Berger, 1969). Excessive nitrogen fertilization often results in shorter, highly branched stems, and also disproportionately thick stems, both of which reduce fibre quality. Excess nitrogen has also been linked to a higher incidence of lodging (Berger, 1969; Sultana, 1983; Hocking et al., 1987), although Easson and Long (1992) identified no such link in their research. Findings reported by Rowland (1980) are not consistent with the results of Dempsey (1975), which suggest that excess nitrogen can result in lower fibre yield and quality as well as increased lodging. Nitrogen level also affects plant density, plant height, and seed yield of flax (Lafond, 1993). Rowland (1980) reported an increase in flax straw production with elevated rates of nitrogen fertilizer. Sheppard and Bates (1988) report that the response of flax, and numerous other crops, to nitrogen fertilization is dependent on local weather conditions and seeding date.

A variety of nitrogen recommendations for fibre flax can be found in the literature, ranging from 30-40 kg ha $^{-1}$, up to 100 kg ha $^{-1}$ (Berger, 1969; Hocking et al., 1987; Lockhart & Wiseman, 1988). Easson & Long (1992) indicate an upper limit of 25 kg ha $^{-1}$ as the recommended rate prior to 1959, and in their own research have linked increasing rates of nitrogen fertilizer (up to 50 kg ha $^{-1}$) to increased stem diameters and higher overall straw production.

Phosphorus (P) also affects flax fibre quality, by influencing stem length and thickness, as well as the proportion of fibre bundles in the stem (Berger, 1969). Excess phosphorus has been correlated to higher branching in flax, shorter stems, and lower tensile strength of fibres (Berger, 1969). However, some reports suggest that elevated phosphorus can offset some of the negative effects of excess nitrogen (Berger, 1969). Grant and Bailey (1989) reported an increase in dry matter yield of flax under high phosphorus levels. Hocking et al. (1987) reported that phosphorus placement is as important as rate of application, since flaxseed germination appears to be lower in the presence of high phosphorus. Phosphorus recommendations in fibre flax production range from as little as 10-30 kg ha $^{-1}$ (Hocking et al., 1987) to as much as 60-100 kg ha $^{-1}$ (Berger, 1969; Lockhart & Wiseman, 1988).

Potassium (K) has been suggested to have a substantial impact on stem size as well as influencing both fibre length and quality in terms of strength and elasticity (Berger, 1969). Adequate potassium is also necessary for the field retting process (Berger, 1969). A range of 67 to 180 kg K ha $^{-1}$ has been reported for fibre flax production (Berger, 1969), however Lockhart & Wiseman (1988) suggest as little as 50 kg ha $^{-1}$ while Hocking et al. (1987) in their literature review, suggested that 20-30 kg ha $^{-1}$ be used. Hocking et al. (1987) also report conflicting results as to the sensitivity of flax cultivars to potassium, with some cultivars showing lower emergence rates in the presence of 20 kg ha $^{-1}$ potassium sulfate.

1.5.3. Pests of fibre flax

1.5.3.1 Weeds

Fibre flax competes poorly with weeds due in part to its tall, unbranched architecture and relatively low leaf area index (Hocking et al., 1987; McSheffrey et al., 1992; McHughen & Holm, 1995). Weed control strategies are therefore essential since there is little in the way of crop canopy formation in the early stages of crop development (Maddens, 1989). This lack of canopy formation allows weed seeds to germinate and develop rapidly (Maddens, 1989; FCC, 1996). The high density of fibre flax, usually 2000 plants m^2 (Robert, 1996; Stephens, 1997) is an important means of allowing fibre flax seedlings to compete more effectively with weeds (Stevenson & Wright, 1996). The relatively short growing season of 100 days also does not leave much time for fibre flax to recover from reduced growth due to strong weed competition (Maddens, 1989). An additional problem created by the presence of weeds involves the contamination of the harvested fibres with less desirable weed stalks (Marshall et al., 1995). There are a number of herbicides currently registered for use in oilseed flax in Western Canada and Ontario. Some of these include quizalofop-ethyl (Assure®), bentazon (Basagran®), bromoxynil/MCPA (Buctril M®), diclofop-methyl (Hoe-Grass®), clopyralid (Lontrel®), MCPA, sethoxydim (Poast®), clethodim (Select®), and trifluralin (Treflan®) (Courteney, 1986; 1987; McHughen & Holm, 1995; FCC, 1996; Anon., 1997; Anon., 1998). There are also a number of reports of transgenic work being done in oilseed flax leading to various degrees of herbicide tolerance (McSheffrey et al., 1992; McHughen & Holm, 1995; Wall & Kenaschuk, 1996).

1.5.3.2 Diseases

The very high plant densities employed in fibre flax fields (1800-2000 plants m^2), as well as the favourable microclimate in such stands, make flax highly susceptible to cryptogamic disease infection and development (Beaudoin, 1989). There are three main categories of fibre flax diseases found in Europe: stem desiccation diseases, damping off diseases, and diseases associated with rot (Beaudoin, 1989). Stem desiccation diseases and the causal organisms include firing (*Pythium* spp.), yellows of flax (*Phoma linicola* spp.), fusariose (*Fusarium oxysporum* f. sp. *lini*), scorch (*Polyspora lini*), and rust

(*Melampspora lini*) (Beaudoin, 1989). Organisms causing damping off diseases include *Botrytis cinerea*, *Phoma linicola*, *Fusarium* spp., *Alternaria linicola*, and *Colletotrichum lini* (Beaudoin, 1989). Stem-rot is a rotting disease involving the organism *Botrytis cinerea* (Beaudoin, 1989).

A number of diseases associated with oilseed flax are found in Western Canada (Martens et al., 1994; Anon. 1998). It is likely that at least some would be a threat to fibre flax production in Québec, since fibre flax cultivars belong to the same species as oilseed cultivars (Sultana, 1983). The major diseases of flax in Western Canada according to the Flax Council of Canada (FCC, 1996) are rust, caused by *Melampsora lini,* fusarium wilt caused by *Fusarium oxysporum* f. sp. *lini*, pasmo, caused by the fungus *Septoria linicola,* and seedling blight and root rot caused by a number of soilborne fungal species including *Fusarium*, *Rhizoctonia*, and *Pythium* (Martens et al., 1994). Other organisms causing relatively minor damage to oilseed flax crops in Western Canada include *Alternaria linicola*, *Phoma exigua*, *Selenophoma linicola*, *Colletotrichum* spp., and *Scerlotinia sclerotiorum* (Martens et al., 1994; FCC, 1996; Anon. 1998).

Common strategies for dealing with these organisms include the use of certified seed and recommended cultivars, crop rotation, and seed treatment with fungicides (Sultana, 1983; FCC, 1996). Fungicides currently registered for use in oilseed flax in Western Canada include carbathiin (Vitavax® Single Solution), carbathiin/thiram (Vitavax® Powder or Vitaflo®-280), carbathiin/thiram/lindane (Vitavax® Dual Powder), and maneb (N-M Drill Box Seed Treatment Powder) (FCC, 1996; Anon., 1998).

1.5.3.3 Insects

In Europe there are two major insect groups than can damage to fibre flax. These are the flea beetles *Longitarsus parvulus*, and *Aphtona euphorbiae*; and the thrips *Thrips angusticeps* and *Thrips linarius* (Beaudoin, 1989). Thrips are important insect pests which kill growing points of developing flax plants thereby stimulating branching and reducing main stem fibre quality (Sultana, 1983). Moreover, lower overall fibre yield often results from these attacks also (Sultana, 1983).

There are a number of insecticides currently registered in Saskachewan for use in fibre flax including permethrin (Ambush®), dimethoate (Cygon/Lagon® or Hopper Stopper®), deltamethrin (Decis®), trichlorfon (Dylox®), methomyl (Lannate®), chlorpyrifos (Lorsban/Pyrinex®), malathion (Malathion®), cyhalothrin-lambda (Matador®) (Anon., 1998). A number of products may be tank mixed and applied with herbicides, according to label specifications (Anon., 1998).

1.5.4. Growth regulators

It is not uncommon to apply growth regulators or retardants to flax to help prevent excessive lodging and thus improve crop harvest efficacy (Meijer et al., 1989; Easson, 1989). Much research on the use of growth retardants (e.g. chlormequat and ethephon) in fibre flax production has been carried out in the Netherlands and Belgium (Maddens, 1989; Meijer et al., 1989).

1.5.5. Harvesting and yield

The time from seeding to harvest of fibre flax is 85-100 days (Roseberg, 1996; Stephens, 1997). Yields have been reported as retted flax in t ha $^{-1}$, fresh or dry matter in t ha $^{-1}$, or as fibre yield in t ha $^{-1}$ and yields of fibre generally account for approximately 25% of the total biomass yield in technologically advanced production areas (e.g. France, Belgium) (Roseberg, 1996). Fibre yields in Western Europe can range from 1500-2000 kg ha $^{-1}$ (Roseberg, 1996), which translates to fresh biomass yields of between 6000-8000 kg ha $^{-1}$ (Stephens, 1997). In Eastern Europe, yields are commonly only half the amounts obtained in Western Europe, due in part to the use of different cultivars and less efficient harvesting technologies (Roseberg, 1996). Long fibres are the more desirable component of the yield, and the percentage of long fibres recovered in Eastern Europe tends to account for only 30% of total fibre yield whereas long fibre percentages for Western European countries accounts for 60% of total fibre production (Sultana, 1983). A study in Québec from 1995 to 1997 found long fibre percentages to be 15 % of total fibre production, which is comparable and even favorable to that found in Western European fibre flax (Robert, 1997; 1998). According to Foster et al. (1997; 1998), fibre length is far less an important factor in fibre flax destined for industrial application than for linen production.

The statewide average fibre yield in Oregon, USA, between 1925-1951 ranged from 1.3- 5.1 tonnes ha $^{-1}$ dry matter, or 260- 1020 kg ha $^{-1}$ fibre (Hurst et al., 1953; Roseberg, 1996). Fibre yields in Oregon in 1995 amounted to 1200 kg ha $^{-1}$ (Roseberg, 1996). In Québec field studies from 1995-97, retted straw yields of 3.5 to 8.5 t ha^{-1}, or potentially 1.16 to 2.83 t ha^{-1} of fibre were obtained (Robert, 1996; 1998).

1.6. Flax processing

One of the foremost differences between flax and many other agronomic crops is that final yield and quality is strongly linked to post-harvest management (Easson & Malloy, 1996). There are a number of unique and critical processes which fibre flax must undergo during harvesting and processing. These processes as well as the machinery used, have changed very little during the last century (Hann & Holme, 1989). Harvesting of fibre flax occurs prior to seed ripening, often after one third (Hemeryck, 1994; Robert, 1996) to two-thirds (Stephens, 1997) of the leaves have been shed. Harvesting is best accomplished with a specialized machine which uproots the plants, since the valuable fibres extend below the soil surface (Sultana, 1989).

Harvesting may be followed by a rippling procedure in the field, during which the seeds are removed and used as a by-product (Keijzer, 1989). If the seeds are not removed in the field, they will be removed later during processing. The flax is then laid on the bare soil in the field where it is left for a period of 2-5 weeks to ret, depending on the climatic conditions (Hann & Holme, 1989; Meijer et al., 1995; Stephens, 1997). This traditional retting process accounts for 75% of world fibre production (Sultana, 1983). This method involves a process of semi-controlled rotting, in which microorganisms, primarily *Clostridium* spp., degrade the middle lamella and adhesive pectins of the cell walls, freeing the fibres (Langer & Hill, 1991; Hemeryck, 1994; Stephens, 1997). This process is known as dew retting, and requires damp, humid environmental conditions, alternating with warmer dry conditions (Sultana, 1989; Meijer et al., 1995). There is some risk associated with dew retting, since it is highly dependent on climatic conditions (Sultana, 1989; Ulrich & Laugier, 1995). More technologically advanced methods of retting take place in large tanks of warm water, where temperature and pH can be more easily controlled, and enzymes specific to the retting process may be added (Ulrich & Laugier, 1995; Niedermann, 1999). The downside to water or tank retting is that highly toxic effluents are produced, and tend to be difficult to dispose of (Niedermann, 1999). This procedure is currently being researched in Belgium and Ireland, and is only practiced in China and Eastern Europe where environmental laws are minimal (Niedermann, 1999). Lockhart & Wiseman (1988) describe a method used in Northern Ireland and Scotland involving the desiccation of the flax through the use of the non-selective herbicide glyphosate (Roundup®), four weeks after flowering. The crop is left standing in the field to ret for 4-6 weeks, and is then mechanically uprooted so that the roots can dry prior to baling. Similar work has been carried out by Stephens (1997) in Connecticut, USA.

Scutching is a process involving the mechanical beating and bending of the fibrous stems, in order to separate the fibres from the xylem, and the rest of the cell wall material (Potter & Corbman, 1967; Stephens, 1997). Scutching is made easier and is more efficient if the retting process was successful (Sultana, 1989). The next step in the processing of flax fibres is hackling, which is essentially the mechanical combing of fibres (Potter & Corbman, 1967), to help remove any cell wall and xylem remnants, as well as to separate the longer fibres (line) from the shorter fibres (tow) (Ulrich & Laugier, 1995).

The long flax fibres are then ready for spinning or weaving into threads or fabrics, whereas the shorter fibres may be used for paper production or other industrial purposes.

1.7. Present distribution

The wide distribution of fibre flax, in both tropical and subtropical climates, is due in part to its relatively early domestication by humans, and dual roles as oil and fibre producer (Bishop et al., 1983; Lee, 1987). Today, linen flax cultivars are commonly grown in cooler, temperate climates such as the former Soviet Union, China, and Europe (Marshall et al., 1989). The oilseed flax cultivars are found in slightly warmer climates, but may be found growing in Western Canada, the USA, South America, India, and the former Soviet Union (Marshall et al., 1989; Langer & Hill, 1991; Maiti, 1997). A total of 8 million ha of flax are grown worldwide each year, however, the bulk of this is oilseed flax (Bolton, 1995). In 1993, under a million ha of fibre flax was produced in the world, with the largest producers being Russia (335,000 ha), Ukraine (127,000 ha), Belarus (120,000 ha), China (93,000 ha), and France (50,000 ha) (Roseberg, 1996). The combined area under fibre flax in France and Belgium in 1990 was 71,000 ha, however this area dropped to less than 40,000 ha within a few years as economic turmoil as felt in Japan, a major importer of fibre flax (Scholz, 1995). Areas for fibre flax production in other European countries are relatively limited. For instance, Germany grew fibre flax on only 825 ha in 1992 (Scholz, 1995). Fibre flax occupied 4,300 ha in 1988 in Estonia, and only 400 ha by 1994 (Kessler, 1994). Fibre flax production in Latvia has oscillated from 63,600 ha in 1938, to 7,700 ha in 1992, and to 1,000 ha in 1993 (Stramkals, 1994).

1.8. Future outlook

1.8.1. The growing need for fibre

World demand for fibre has increased dramatically during the past decade, due in part to strong demands from the Association of South-East Asian Nations (ASEAN) (Bolton, 1995). The large majority of plant fibres produced in the world currently originate from trees. However, recent political events in major wood producing countries such as Canada, the USA, and the former Soviet Union have led to a leveling off of production, rather than to the increases predicted by the Food and Agriculture Organization (FAO) in 1990 (Bolton, 1995). The demand for fibres grown on agricultural lands will inevitably increase as long fibre, annual crops such as flax become more attractive than longer rotation forestry production systems (Bolton, 1995). In fact, fibre flax research in Europe has increased dramatically in recent years as demand for natural fibres continues to escalate around the world (Marshall et al., 1995; Palleson, 1996; Domier, 1998; Foster et al., 1997; 1998).

1.8.2. Current and potential flax markets

Fibre flax plants produce superior quality bast fibres, used in the manufacture of high quality garments and linen (Berger, 1969; Roseberg, 1996). In recent years, technology has allowed flax fibres to be blended with other fibres and synthetics, making flax fibres more appealing to the garment manufacturing industry (Ulrich & Laugier, 1995). There exist other interests in flax fibres, including making use of the straw by-product from the production of oilseed flax, but also on industrial applications for fibre flax (Palleson, 1996; Akin et al., 1996; Domier, 1998; Foster et al., 1997; 1998).

Breeding efforts to develop dual-purpose oil/fibre cultivars, with the fibres being used for industrial purposes is ongoing (Foster et al., 1997; 1998).

In Western Canada in 1997, 1,250,000 tonnes of flax straw were produced as a by-product of linseed production, on 831,000 ha of land (Domier, 1998). Ecusta Fibres and Sweitzer-Mauduit Inc. purchased approximately 15-20% of the straw, which was used primarily for cigarette paper production (Domier, 1998; Niedermann, 1999). A number of smaller companies are beginning to process flax straw for industrial purposes, however over a million tonnes per year is being burned since there is no market for it (Domier, 1998).

There is growing interest from other areas of the industrial sector for fibre flax, such as the use of flax fibres in the construction of reinforced particleboard (Domier 1996). Research into flax fibres as insulation material is currently underway at the University of Alberta (Domier, 1996).

The potential uses of fibre flax are numerous. In Europe, flax fibres have been used in combination with other natural fibres in the manufacture of automotive door panels, upholstery, roof liners, and molded products for use in dairy plants and food processing facilities (Domier, 1996). Products made with flax fibres tend to exhibit excellent strength and durability, as well as moisture resistant traits (Domier, 1996).

In recent years, the popularity of flaxseed as a health food supplement has increased dramatically (Carter, 1993). Medical research has shown possible anti-cancerous effects of the seed (Davin & Lewis, 1998; Rickard et al, 1998; Westcott et al., 1998). In addition, flaxseed contains high levels of dietary fibre, protein and potassium, which may have anti-inflammatory effects and some degree of anti-malarial activity (Carter, 1993; 1998). There is also strong evidence that flaxseed aids in lowering blood cholesterol (Clark & Parbtani, 1996; Cunnane et al., 1996) but flaxseed for human consumption can only be obtained from specific cultivars.

It appears that there should be no shortage of markets for flax fibres, either long or short, or seeds produced from fibre flax plants, especially as improved and rapidly changing technology is helping to discover new uses for flax and its by-products.

1.9. Thesis objectives

Québec's moist, cool temperate climate is likely better suited to fibre flax production than Western Canada, especially for the field retting process. Western Canadian climatic conditions tend to be too dry for optimal retting, an essential step to minimize the costs of production. Prior to the second World War, flax production was widespread in Québec, and a total of 18 processing mills were active in 1942 (Hutchinson, 1948). Fibre flax is a potential cash crop for Québec producers, however there is a paucity of information on fibre flax management under Québec growing conditions. A fibre flax project was initiated in 1995 in the Chateauguay valley south of Montréal (Québec), lead by the Ministère de l'Agriculture, Pêcheries, et Alimentation du Québec (MAPAQ) (Robert, 1997; 1998). Five farmers were contracted to grow fibre flax by Mr. Timothy Niedermann of U.S. Flax and Linen Co., under the guidance of a consultant, Mr. Eric Laugier, and Mr. Louis Robert, an agronome working for MAPAQ (Robert, 1997; 1998). The goal of the project was to assess the feasibility of fibre flax production in Québec as an alternative crop (Robert, 1998).

In the summer of 1997, small plot trials were initiated at Macdonald Campus, McGill University, Ste. Anne-de-Bellevue, Québec, to examine in more detail a variety of factors involved in fibre flax production. Specifically, the goals of the research were to:

1) assess the ability of modern European fibre flax cultivars to grow under Eastern Canadian climatic conditions, and yield acceptable quantities of high quality fibre.
2) examine the effects and interactions of depth of seeding with soil packing (rolling) prior to vs. after seeding, or not at all, on the establishment and yield characteristics of fibre flax (cv. Ariane) in a conventional tillage system.
3) evaluate the performance of one of the standard European fibre flax cultivars (cv. Ariane) in three different tillage systems: conventional tillage, minimum tillage, and zero tillage, in terms of establishment and yield characteristics.

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Connecting Text

The general introduction in the previous chapter indicates a wealth of knowledge regarding fibre flax production and utilisation, however, little or any may be applicable to North America. Fibre flax cultivars of European origin must be evaluated scientifically in order to gauge their potential success or failure in North American conditions. The following chapter describes research conducted to evaluate a number of European fibre flax cultivars in Southern Québec and Eastern Ontario, Canada, and the ensuing recommendations.

Chapter 2. Evaluation of European Fibre Flax Cultivars for Potential Introduction into Eastern Canada

2.1. Abstract

Research was conducted at a number of sites at Macdonald Campus of McGill University in 1997 and 1998, and at two sites in Eastern Ontario in 1998, to assess the performance of a total of 11 fibre flax cultivars of European origin. Five cultivars were tested in 1997 at three sites at Macdonald Campus and the results from two sites indicated no significant differences between cultivars for any of the parameters measured. At the third site, significant differences were found in mean plant density and mean plant height between cultivars. The French cultivar 'Ariane' was the best performing and most consistent of the cultivars tested in 1997. Results also indicated a possible interaction between cultivar and site. Results obtained in 1998 studies assessing the performance of ten cultivars at Macdonald Campus and Kemptville, Ontario, and eight cultivars at Winchester, Ontario, indicated significant differences between the cultivars for all of the parameters measured. These included plant density, branching ratio, stem diameter, fresh and dry weights, and mean plant height at various times during the growing season. The cultivar 'Ariane' was again the most consistent performer across locations, leading us to suggest that it be used as a standard against which other cultivars be tested for potential use in Eastern Canada.

2.2. Introduction

Fibre flax (*Linum usitatissimum* L.) is an ancient crop that is currently enjoying a resurgence of interest in various parts of the world (Kozlowski & Manys, 1994; Akin et al., 1996; Smeder & Liljedahl, 1996; Foster et al., 1997; 1998). This crop was of economic significance in Eastern Canada and parts of the United States until just after World War II (Robert, 1995; Stephens, 1997b). During the post-war years, loss of government subsidies, competition from newly developed synthetic fibres, as well as technological advancements promoting the adoption of various other natural fibres, helped to reduce and eventually halt fibre flax production in North America (Roseberg, 1996; Stephens, 1997b). Not surprisingly, little in the way of research or breeding programs have been carried out on fibre flax in North America from the 1950's until more recently. During these years however, fibre flax has maintained a greater degree of popularity in Western Europe, where breeding programs and technological improvements have led to highly efficient production systems (Roseberg, 1996).

Fibre flax clearly enjoys some degree of niche market status, and recent technological advancements enabling flax fibres to be easily blended with other fibres has broadened that appeal (Ulrich & Laugier, 1995). There has also been increased interest from a variety of manufacturing and industrial sectors in the fibres derived from the flax plant (Akin et al., 1996; Smeder & Liljedahl, 1996; Foster et al., 1997; 1998). Although the reasons behind the increased demand for flax fibres are clear, there has been some doubt as to where the increase in production will occur. Government subsidies to European producers in countries such as Belgium and France have succeeded in supporting the fibre flax industry for many years (Laugier, 1997). European farmers require ever greater profits from their land, while international trade agreements are beginning to make heavy subsidies more controversial (Laugier, 1997). Although fibre flax production occurs in other areas, notably Eastern Europe and China, local production methods tend to be antiquated with abundant and inexpensive human labour compensating for dated local technology (Roseberg, 1996). Thus, North America appears to be well placed as the obvious location where the added fibre flax production can take place. In North America, there is an abundance of land and technologically advanced production systems for other crops, as well as an agricultural history that already includes fibre flax. However, there are a number of important production concerns that need to be addressed through research prior to the re-introduction of this crop into such North American regions as Québec. One major factor of interest that constitutes the objective of this research, was to assess the ability of modern widely grown European cultivars to adapt to Eastern Canadian growing conditions, while maintaining acceptable levels of high quality fibre.

2.3. Materials and methods

The research was carried out during the 1997 and 1998 growing seasons at Macdonald Campus of McGill University in Ste. Anne-de-Bellevue, Québec, Canada, and in 1998 at Kemptville and Winchester, in Eastern Ontario, Canada. In 1997, there were three experimental sites at Macdonald Campus (45° 25' 45" N lat., 73° 56' 00" W long.). The first site was located on a St. Amable loamy sand soil (well drained, Gleyified Humo Ferric Podzol; pH 5.0-5.7) (Lajoie, 1960), the second was located on a Ste. Rosalie clay soil (poorly drained, Dark Gray Gleysolic; pH 5.6-6.2) (Lajoie, 1960), and the third site was located on a Bearbrook clay soil (poorly drained, Dark Gray Gleysolic; pH 5.6-6.4) (Lajoie, 1960). Previous cropping regimes in each location were: Kura clover in 1996 at the St. Amable site, and fallow in 1995. The Ste. Rosalie site was fallow in 1996, and was in alfalfa for the three previous years. The Bearbrook clay site was in wheat in 1996, and corn in 1995. The soil type at the Macdonald site in 1998 was a St. Bernard loam (well drained, Melanic Brunisol; pH 6.11) (Lajoie, 1960), which was in barley in 1996 and red clover in 1995. The first of the Eastern Ontario sites in 1998 was located on a Grenville sandy loam soil (well drained, Melanic Brunisol; pH 6.5-7.0) (Lajoie, 1960) at Kemptville Agricultural College in Kemptville, Ontario, which had been sown to wheat in 1997. The second site was located on a Chateauguay clay loam soil (slightly imperfectly drained, Gray Brown Podzolic; pH 6.2-6.5) (Lajoie, 1960) at the Kemptville Agricultural College Research Station located in Winchester, Ontario, and was in corn the previous year.

A total of 11 fibre flax cultivars (Table 2.1) of European origin were compared in a series of six experiments during 1997 and 1998. Land preparation at all sites in both years included fall plowing followed by spring disking and harrowing prior to seeding. In both years, 200 kg ha $^{-1}$ of balanced fertilizer (20-10-10) was incorporated prior to seeding. Climatic data (temperature, rainfall, and growing degree days) for both years at the Macdonald site were recorded by an automatic weather station at the Agronomy Centre. These data are presented in Appendix 2.1. Weather data for the Kemptville site was recorded by an automatic weather station, and this is reported in Appendix 2.1. Although weather data was not available for the Winchester site, however weather patterns likely don't differ greatly from Kemptville, which is less than 50 km to the west.

A germination test was performed in the spring of 1998 to determine any potential differences due to differential seed size or viability between the cultivars. A random sample of seeds was used for each cultivar, from which a sub-sample of 160 seeds was counted and seeds placed in lots of 20 in each of eight petri dishes. The dishes were placed randomly in a growth chamber set at 20° C day/14° C night temperature regime, in the dark. Germinated seeds were removed from the plates every 24 hours for three days. This test was ended on day four when no seed germination was recorded.

Five cultivars were tested at Macdonald in 1997 at two sites, and four of these same cultivars tested at the other site. Plots were seeded on May 24 using a Carter forage plot seeder having a row spacing of 15 cm, into plots measuring 1.5 m x 4 m. The experimental design was a randomized complete block with four blocks and one replicate/treatment/block. A standard seeding rate of 100 kg ha $^{-1}$ was used for all cultivars. In 1998 at the Macdonald site, a customized forage seeder with a row spacing of 18 cm was used for seeding on April 30. Differential seeding rates were used based on seed size, to obtain fibre flax populations of approximately 2000 plants m^2. Due to the late arrival of new cultivars from France, these rates were not adjusted for percent germination, however a germination test was performed later as described above. Plot size was 1.5 m x 5 m, and the experimental design was a randomized complete block with four blocks, with one replicate/treatment/block. At the Winchester site, the Carter forage plot seeder (row spacing 15 cm) as in 1997 was used, and the plots were seeded on May 1. Plot size was 1.5 m x 5 m, and the experimental design was a randomized complete block with three blocks, with one replicate/treatment/block. At the Kemptville site, a customized turf seeder was used for seeding, resulting in a broadcast-style establishment pattern rather than rows, in plots measuring 2 m x 5 m. The experimental design was a randomized complete block with four blocks, with one replicate/treatment/block.

In order to control weed infestations, herbicide applications were made in 1997 and 1998 as required. In 1997, all three trials were sprayed post-emergence with bromoxynil/MCPA (Buctril M®) + sethoxydim (Poast®) + mineral oil surfactant at rates of 560 g ai ha $^{-1}$ + 276 g ai ha $^{-1}$ + 2 L ha $^{-1}$, for the control of broadleaf and grass weed species. Bentazon (Basagran Forte®) was applied later at a rate of 1.08 kg ai ha $^{-1}$ for the control of yellow nutsedge (*Cyperus esculentus* L.). In 1998, the Macdonald trial was sprayed with fluazifop-p-butyl (Venture®) + mineral oil surfactant at a rate of 0.7 kg ai ha $^{-1}$ + 0.5 % v/v for the control of quackgrass (*Elytrigia repens* (L.) Nevski). Bentazon was later applied at the rate of 1.08 kg ai ha $^{-1}$, for the control of broadleaf weed species visible in the plots. The Winchester trial was heavily infested with wild mustard, and due to an interaction between time constraints and unfavourable weather conditions was not sprayed. The plots were later hand-weeded however, with an emphasis on minimizing physical damage to the flax. The Kemptville trial did not require spraying due to a lack of weeds, or perhaps due to the broadcast style seeding which gave the crop a competitive advantage. All herbicide treatments followed recommendations for oilseed flax in Publication 75: Guide to Weed Control (Anon., 1997).

2.3.1. Data collection

2.3.1.1. 1997 Growing season

The data collected from all experiments aimed to assess the feasibility of fibre flax production in Eastern Canada, using cultivars of European origin. Of main interest were the yield and quality of fibres produced. Fibre quantity and quality were to be assessed by professionals at the Gilflax Inc. flax scutching mill in Valleyfield, Québec.

Data collection in 1997 included average plant height (measured from soil level to the uppermost growing point of each plant) per plot, and was recorded prior to harvest. The plot average was the mean of two observations where a group of plants (approximately 8-12) were held together against a meter-stick, and their average height estimated as one value.

Plant densities in each plot were assessed twice within a 30 cm x 30 cm quadrat. Within each of these quadrats, the number of plants that had branches within the first 50 cm of stem was also counted. The number of plants with branches was then divided by the total number of plants in the sample, resulting in a "branching ratio" for each treatment or plot. The plant density data and the branching ratio values were transformed prior to analyses using square root and square root + 1 to satisfy the normality requirement of ANOVA (Gomez & Gomez, 1984).

Stem diameters (measured just above the soil level) were assessed on 25 plants in each plot using a Marathon 150mm electronic digital caliper (Marathon Management Co., Richmond Hill, Ont.). Due to significant variability, the mean stem diameter for each plot was used in analyses, and these mean data did not require transformation to satisfy the normality requirement of ANOVA.

"Retted" straw yield was also assessed (see General Introduction for description of the retting procedure). Since the sample size required for quality analysis by the scutching mill was unknown, almost the entire plot (4 m^2) was harvested in 1997. The plants were uprooted by hand when one half to two thirds of the lower leaves had been shed, and capsules were beginning to turn brown in colour (Stephens, 1997b). The soil was shaken from the roots, and the plants were then laid in the field for approximately two weeks, after which they were turned over by hand, and were left in the field for approximately ten days more. The retted plot yield was then recorded for each cultivar by weighing, and the plants bulked by cultivar for transportation to the scutching mill.

2.3.1.2. 1998 Growing season

Data collection in 1998 was slightly modified for a number of reasons. Most importantly, Gilflax Inc. was experiencing management difficulties and was unable to assess the fibre quantity and quality of our samples collected in 1997, also implying that any 1998 samples would also not be assessed.

Moreover, due to the difficulty in determining the stage at which the flax was adequately retted and the negative impact on quality associated with possible errors in this process (Hemeryck, 1994; Robert, 1996), fresh and dry weights were recorded in 1998. Flax plants were harvested and fresh weights determined within a randomly placed quadrat measuring 55 cm x 53 cm in each plot. A 200 g sub-sample of each plot was dried to a constant weight in a forced air dryer at 65° C, and the dry matter content determined.

Data collection at the Macdonald site included various phenological parameters such as recording the number of days to emergence for each variety, number of days to flowering, and number of days to harvest. At all sites, stem diameters were measured on a random sub-sample of 25 plants per plot. Branching and density data, as in 1997, were recorded twice within two 25 cm x 12 cm strips in each plot, and the number of plants with branches in each sample was also recorded, and data transformed as described for 1997. Average plant height per plot was recorded three, six and nine weeks after emergence using the same methodology as in 1997, except that four averages per plot were used rather than two. The only differences between sites in the parameters measured in 1998 were that heights at the Kemptville site were observed at six and eight weeks post-emergence only, and the branching data at the Winchester site was lost.

All data collected were subjected to analysis of variance (ANOVA) using the GLM procedure in SAS (SAS Institute, 1985), to identify any main effects due to cultivar on the parameters described above. Due to inconsistencies in the number of cultivars per site, and differential seeding rates between years, cultivar x location interactions as described by Fehr (1987) could not be assessed. Significant results ($P<0.05$) were then subjected to a Tukey's HSD means comparison procedure (Motulsky, 1995), to identify specific differences between treatments.

2.4. Results

2.4.1. Germination test

Seed weight was found to vary significantly ($P < 0.001$) between cultivars. Viking seeds were the heaviest (6.5 g per 1000 seeds) and Belinka seeds were the lightest (4.9 g per 1000 seeds) (Table 2.2). Germination was rapid, with the bulk of the seeds germinating in less than 24 hrs for all cultivars except Belinka (Table 2.2). There was also a significant ($P < 0.05$) difference in relative germination, with Belinka displaying only 69% germination, and all other cultivars ranging from 90% (Escalina) to 100% (Viola and Diane) (Table 2.2).

2.4.2. 1997 field trials

The spring of 1997 was cooler and precipitation received in April was 50% above average levels (Appendix 2.1). Temperatures were below average until June, and the growing season had fewer growing degree days (base of 5° C) than normal (Appendix 2.1). Rainfall was exceptionally high in July and August, making harvesting and retting difficult and complicated (Appendix 2.1).

2.4.2.1. St. Amable sandy loam site

Analysis of variance performed on all data collected at this site showed no significant ($P < 0.05$) differences between cultivars for plant density, branching ratio, stem diameter, plant height, or retted weight (Table 2.3). The popular French cultivar Ariane, was the tallest variety, exhibited a greater degree of branching, and had the greatest stem diameter of all the cultivars tested (Table 2.3). This did not however translate into increased straw yield, as Ariane was the fourth highest yielding cultivar (8.9 t ha $^{-1}$) (Table 2.3). Ilona was the highest yielding cultivar (10.7 t ha $^{-1}$), likely due to the higher plant densities observed in these plots (Table 2.3). Ilona also exhibited on average, a lower degree of branching, as well as lower stem diameters than the other cultivars, although these differences were not significant (Table 2.3).

2.4.2.2. Ste. Rosalie clay site

There were no significant ($P \geq 0.05$) differences in retted straw weight between the cultivars (Table 2.3). There was a significant ($P < 0.05$) difference in plant density between the different cultivars (Table 2.3). Escalina plots had the highest plant density at 1182 plants m^2, while the Evelin plots exhibited the lowest average plant density with only 913 plants m^2 (Table 2.3). There was a highly significant ($P < 0.01$) difference in average height between cultivars (Table 2.3). Ariane plants averaged 99.5 cm in height, and Ilona plants were the shortest , averaging 82.8 cm in height (Table 2.3). Ariane exhibited the highest degree of branching although there was no significant ($P \geq 0.05$) difference in branching ratio between cultivars (Table 2.3). Plants of the Viola cultivar had greater, but not significantly different, stem diameters than the other cultivars, while

Evelin plants had the most slender stems (Table 2.3).

2.4.2.3. Bearbrook clay site

There were no statistically significant ($P \geq 0.05$) differences between the cultivars in retted straw weight (Table 2.3). Ariane yielded the most retted straw per hectare (7.4 t ha^{-1}) and Evelin the least (6.6 t ha^{-1}) (Table 2.3). Moreover, there were no significant ($P \geq 0.05$) differences in average plant height between cultivars (Table 2.3). There was only a 4.5 cm difference between the tallest and shortest cultivar, with Ariane averaging 85.5 cm, and Escalina averaging 81 cm in height (Table 2.3). There were no significant ($P \geq 0.05$) differences in plant density between cultivars (Table 2.3). Ariane plots had the highest densities (1244 m^2) and Viola plots had the lowest densities (1183 m^2) (Table 2.3). Branching patterns did not differ significantly ($P \geq 0.05$) between cultivars (Table 2.3.). Escalina exhibited the highest degree of branching, and Viola the lowest (Table 2.3). Stem diameters between cultivars also did not differ significantly ($P \geq 0.05$) (Table 2.3). Viola exhibited the thinnest stems (1.8 mm), while Ariane, Escalina and Evelin all had relatively similar stem diameters (1.95, 1.98 and 1.94 mm, respectively) (Table 2.3).

2.4.3. 1998 field trials

The month of April in 1998 was much warmer and drier than average (Appendix 2.1). The mean temperature was 2° C above normal, with only a quarter of the normal rainfall, thus allowing seeding to occur earlier than planned (Appendix 2.1). In fact, temperatures were above normal every month from April to September, except for July, which was one degree below normal (Appendix 2.1). The same pattern was observed for rainfall, with every month receiving below normal levels, except for June, which had 1.5

times the normal rainfall (Appendix 2.1). The number of growing degree days (base of 5° C) was therefore substantially above average (Appendix 2.1). Temperatures at Kemptville mirrored those at Macdonald throughout the growing season (Appendix 2.1). Precipitation at Kemptville was similar to Macdonald for all months except July and August, where Kemptville had almost twice the precipitation that Macdonald had in each of those months (Appendix 2.1). Due to it's proximity, Winchester climatic conditions were assumed to be similar to the results at Kemptville.

2.4.3.1. Macdonald site

All cultivars emerged within one week of seeding (Table 2.4). Argos and Escalina emerged after five days; Ariane, Diane, Evelin, Hermes, Raisa and Viking emerged after six days; Belinka and Viola emerged after seven days (Table 2.4). Evelin and Viking attained the flowering stage after only 48 days (Table 2.4). Based on visual estimations of 75 % of the plot in flower, the mean across cultivars was 53 days, (Table 2.4). Raisa required 56 days to achieve flowering, the longest of the cultivars (Table 2.4). There was little difference in the number of days to harvest, with an overall mean of 82.8 days required (Table 2.4). Evelin and Viking (the first to flower) required 79 days to harvest, Belinka 82 days, and all other cultivars required 84 days (Table 2.4).

There were highly significant differences between cultivars ($P < 0.05$) for all parameters measured at the Macdonald site in 1998 (Tables 2.5A, B, C). There was a highly significant ($P < 0.01$) difference between cultivars in fresh weight (Table 2.5A), with Ariane, Argos and Escalina all yielding more than 21 t ha $^{-1}$ of fresh straw, while Evelin yielded only 15.2 t ha $^{-1}$ (Table 2.5A). Dry weights also differed significantly ($P < 0.001$) between cultivars (Table 2.5A). Three of the highest yielding cultivars, Ariane, Argos, and Raisa, also had the lowest dry matter contents (38-39%) (Table 2.5A). Evelin, the lowest yielding cultivar, had the highest dry matter content, 46% (Table 2.5A). There were highly significant ($P < 0.001$) differences in plant density between the cultivars (Table 2.5B). Viking and Raisa were the only cultivars whose plant densities averaged more than 2000 plants m^2 (Table 2.5B). Belinka had the lowest plant density at only 967 plants per m^2 (Table 2.5B). Branching ratio was found to differ significantly ($P < 0.001$) between cultivars (Table 2.5B), with Belinka exhibiting the highest proportion of branched plants by far, four times greater than Diane, the cultivar showing the second highest branching levels (Table 2.5B). The branching ratio amongst the nine other cultivars did not differ significantly (Table 2.5B). There were also highly significant ($P < 0.001$) differences between cultivars in terms of average stem diameter (Table 2.5B). Belinka showed the largest stem diameters (2.22 mm), and Viking, the lowest (1.56 mm) (Table 2.5B). There were highly significant ($P < 0.001$) differences in height between cultivars for all of the three sampling dates (Table 2.5C). Viking was the tallest (21.3 cm) four weeks post-emergence and Escalina was the shortest (13.6 cm) (Table 2.5C). By six weeks post-emergence, Belinka was the tallest cultivar at 71.3 cm, and Raisa was the shortest with a mean height of 60 cm (Table 2.5C). Escalina was the tallest cultivar at harvest, measuring 83.3 cm, while Evelin was the shortest, measuring 70.2 cm (Table 2.5C).

2.4.3.2. Winchester site

There were highly significant ($P < 0.001$) differences between cultivars for all parameters measured except stem diameter (Tables 2.5A, B, C). Diane yielded 23.6 t ha^{-1} of fresh straw, while Viking yielded the least fresh straw at only 12.3 t ha^{-1} (Table

2.5A). Viking plants also produced the greatest dry matter content at 44%, and the highest average plant density (1878 plants m^2) (Table 2.5B). Belinka had the lowest average plant density of all the cultivars tested (900 plants m^2) (Table 2.5B). Diane was consistently the tallest cultivar at all three sampling dates, with a mean harvest height of 96.4 cm (Table 2.5C). Stem diameters did not differ significantly ($P \geq 0.05$) between cultivars (Table 2.5B), and branching data was lost for this site.

2.4.3.3. Kemptville site

Fresh weight was the only parameter that did not differ significantly ($P \geq 0.05$) between cultivars at the Kemptville site (Table 2.5A). Dry matter content did vary significantly ($P < 0.01$) between cultivars (Table 2.5A), and ranged from 43% for Viking to 38% for Evelin (Table 2.5A). Plant density also varied significantly ($P < 0.01$) between cultivars (Table 2.5B). Viking plots averaged 1665 plants m^2, while Belinka plots averaged 1170 plants m^2 (Table 2.5B). The branching ratio between cultivars varied significantly ($P < 0.001$) (Table 2.5B), with 2.5 times more Belinka plants having branches than the next most highly branched cultivar, Evelin (Table 2.5B). Mean stem diameter also varied significantly ($P < 0.001$) between cultivars (Table 2.5B), with Hermes having the thinnest stems (1.51 mm), and Viola the thickest stems (1.96 mm) (Table 2.5B). Plant height at both sampling dates varied significantly ($P < 0.001$) (Table 2.5C). At the first sampling date, five weeks post-emergence, the mean height of Belinka plants was 61.0 cm, and 46.8 cm for Evelin plants, which were the shortest (Table 2.5C). At the second sampling date, 8 weeks post-emergence, plants in the Diane plots were the tallest (104.3 cm) and plants in the Raisa plots were the shortest (87.5 cm) (Table 2.5C).

2.5. Discussion

2.5.1. Germination experiments

Some variation in seed size and germinability for a given cultivar may be expected due to such uncontrollable factors as region of seed production and weather fluctuations during a given year, as well as conditions under which seed is stored. This variability has been shown to be true for crops such as corn (Odiemah, 1991), lettuce and tomato (Hampton & Kahre, 1994), and also for many wild plant species (Thompson, 1981). In our case, the popular and widely grown French cultivar Ariane, exhibited a 1000-seed weight of 6.2 g, however this same cultivar has been described elsewhere as having a 1000 seed weight of only 5.5 g (Robert, 1995). Similarly, the Belinka seed used by Québec farmers in 1996 was reported to have had an 89 % germination rate by Gilflax Inc. personnel (Robert, 1996), while germination tests at Macdonald Campus showed only a 69% germination rate for this cultivar. Consequently, the poor performance of the Belinka cultivar on farms in Québec in 1997 was attributed to seeder miscalibration and mis-calculated 1000 seed weights (Robert, 1996), when it may in fact have been due to poor germination levels.

Differential seed weight often results in differential seed viability or seedling vigour (Westoby et al., 1992). Seed weight is closely linked to the quantity of metabolic reserves available to the germinating seedling during early growth (Westoby et al., 1992), and seedlings arising from larger seeds often establish and develop more rapidly (Milberg & Lamont, 1997). The very low 1000-seed weight of the Belinka cultivar (4.9 g) may, therefore, be partly responsible for the lower rate of germination relative to the other cultivars, and the very low populations of Belinka plots in the field trials.

2.5.2. Field trials

Despite a cool spring, experiments in 1997 were seeded later than they should have been. Part of the danger in a late seeding is having to contend with highly variable weather conditions in the early fall during the time of retting, rather than late summer retting when weather patterns tend to be marginally more predictable. Too much rain during retting often results in poor quality fibre (Stephens, 1997) as the flax lies in pools of water in the field.

Results from the 1997 trials suggest that there was little variation in the parameters of interest within the sites due to the different cultivars. As previously mentioned, no significant differences between cultivars in any of the parameters measured were detected at either the St. Amable site or the Bearbrook site in 1997. Mean plant density and mean plant height were the only factors that differed significantly at the Ste. Rosalie site. However, there appears to be some degree of variation between the sites. Plants grown at the Ste. Rosalie site averaged 6 cm taller than at the other sites (Figure 1), and mean plant density was 140 plants m^2 lower than at the Bearbrook clay site (Figure 2). Plant densities were nearly 50% lower at the other two sites compared with the St. Amable site (Figure 2). Mean stem diameter was greatest at the Ste. Rosalie site, while plots at the Bearbrook site exhibited a substantially greater proportion of branched plants (Figures 3 & 4). Soil type may have played a role in these unexpected differences in results, however variability between the sites make the testing of cultivar by site interaction difficult.

Differences between sites in retted straw yield were likely not due to soil differences between the sites. Due to late seeding, the flax was retting on the soil surface in September during heavy rainfall. There was pooling on the surface in the Bearbrook area, keeping the flax wet, requiring a longer drying out period. Yields at the Bearbrook site were likely lower due to this extra drying period, so the retted samples contained less moisture than those at the other sites.

Berger et al. (1969) suggested that medium-heavy loams or clay-loams are optimal for fibre flax production, while Robinson & Cook (1931) concluded that fibre flax yields on heavier soils were consistently greater than on lighter soils. Results from field trials in Québec suggest that lighter soils can allow a more rapid growth, but soil type was not examined as a factor affecting plant height or yield (Robert, 1996).

Generally, yields of retted flax straw were high when using the 7 t ha $^{-1}$ standard suggested by Stephens (1996; 1997a), and by comparing our results with those from trials at the Connecticut Agricultural Experiment Station from 1992-95 (Stephens, 1996; 1997a). Our straw yields were also considerably higher than those reported by Rowland (1980) in fibre flax trials in Saskatchewan. The mean yield of the cultivar Ariane across sites was 8.9 t ha $^{-1}$ in 1997. Assuming a loss of 33% of its fresh weight following retting (Sultana, 1983; Stephens, 1997b), and potentially 25% of the fresh weight equal to pure fibre (Roseberg, 1996), Ariane yielded 2.96 t ha $^{-1}$ of pure fibre. This is greater than the Western European average of 1.5 to 2 t ha $^{-1}$ (Roseberg, 1996). Ilona averaged 10.4 t ha –1 across two sites, or approximately 2.6 t ha $^{-1}$ of pure fibre.

In contrast to 1997 results, findings obtained in the 1998 trials indicate a lower variation in the parameters measured between sites than within sites. Due to differences in methodology between the 1997 and 1998 trials, direct yield comparisons are difficult. The higher seeding rate based used in 1998 based on the 1000-seed weights may partially account for the higher yields obtained in 1998 compared with 1997, (Rowland, 1980; also Couture, unpublished data). Also, the 1998 trials were seeded earlier than trials in 1997, which likely contributed to higher biomass production, since sowing date is known to influence yield (Easson & Long, 1992; also Couture, unpublished data). However, seeding rate should always be based on percent germination and in this case, the rate used for the Belinka cultivar, based on 1000-seed weight, was not adequate due, in part, to low germination, such that the resulting populations were substantially different from densities of the other cultivars. The low plant densities in the Belinka plots were also likely a factor in the significantly higher branching ratios and mean stem diameters observed in these plots.

The cultivar Ariane averaged 21.4 t ha $^{-1}$ of fresh straw across sites in 1998, making it the highest yielding cultivar in our 1998 trials. Assuming a 25% fibre content (Roseberg, 1996), Ariane yielded 5.4 t ha $^{-1}$ in pure fibre. Assuming a loss of 33% of its weight following retting (Sultana, 1983; Stephens, 1997b), the mean yield of retted Ariane flax was approximately 14.3 t ha $^{-1}$ in 1998. The dry matter yield would then be 8.9 t ha $^{-1}$, at an average dry matter content of 38%. This is considerably more than the current Western European average of 1.5-2 t ha $^{-1}$ (Roseberg, 1996). However many of the other cultivars tested do fall into or slightly above this range. Robert (1997; 1998) also reported sites in Québec with yields moderately greater than those of Western Europe. It is important to note that yield is not the only parameter of importance, but fibre quantity and quality are also critical, especially for flax fibres destined for linen production. Unfortunately, these important parameters could not be assessed in this research.

In all of the experiments, straw yields and mean plant height were greater than or comparable to those reported by others attempting to re-introduce fibre flax into North America (Rowland, 1980; Robert, 1995; 1996; Stephens, 1996; 1997a; 1997b). Ariane is presently one of the most popular and widely grown cultivars in Europe, occupying 60 % of the fibre flax acreage in Western Europe (Trouve, 1994). In our trials, Ariane was generally the tallest cultivar, as well as one of the highest yielding, regardless of soil type or geographic location. Its performance in these trials was consistent enough to lead us to suggest it be used as a standard against which to assess the performance of other potential fibre flax cultivars, regardless of the intended final use of the fibres.

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Table 2.1. Cultivars assessed during 1997 and 1998 field trials, by location.

Macdonald-1997	Macdonald-1998	Kemptville-1998	Winchester-1998
Ariane	Ariane	Ariane	Ariane
Escalina	Escalina	Escalina	Escalina
Evelin	Evelin	Evelin	-
Ilona	-	-	-
Viola	Viola	Viola	-
-	Argos	Argos	Argos
-	Hermes	Hermes	Hermes
-	Diane	Diane	Diane
-	Raisa	Raisa	Raisa
-	Belinka	Belinka	Belinka
-	Viking	Viking	Viking

Table 2.2. Varietal seed weights and results of germination experiment.

Cultivar	1000 seed weight (g)	After 24 hrs	After 48 hrs	After 72 hrs	Total # seeds germinated	% of seeds germinated
Diane	6.3 ab	152	8	-	160 a	100
Viola	6.1 bc	130	29	1	160 a	100
Ariane	6.2 ab	158	1	-	159 a	99
Viking	6.5 a	158	1	-	159 a	99
Evelin	5.7 d	132	24	2	158 a	99
Hermes	6.0 bcd	146	11	-	157 a	98
Raisa	5.6 d	121	35	1	157 a	98
Argos	6.2 ab	151	3	2	156 a	98
Escalina	5.8 cd	119	17	8	144 a	90
Belinka	4.9 e	49	44	17	110 b	69
m.s.d.	0.36	-	-	-	6.0	-

a, b, c, d, e Values within a column followed by the same letter(s) do not differ, according to Tukey's HSD test, P = 0.05.
m.s.d. Minimum significant difference.

Table 2.3. Comparison of means for various plant parameters measured from cultivar trials at three sites at Macdonald Campus in 1997.

	Mean plant density (m^2)			Mean branching ratio			Mean stem diameter (mm)			Mean retted straw weight ($t\ ha^{-1}$)			Mean plant height (cm)		
Cultivar	SA	SR	BB	SA	SR	BB	SA	SR	BB	SA	SR	BB	SA	SR	BB
Ariane	589	972 ab	1244	0.04	0.04	0.07	1.88	2.03	1.95	8.9	10.3	7.4	88.3	99.5 a	85.5
Escalina	540	1182 a	1183	0.03	0.03	0.17	1.66	1.96	1.98	8.2	10.0	7.1	86.5	89.0 ab	81.0
Evelin	642	913 b	1094	0.02	0.03	0.05	1.67	1.87	1.93	9.8	9.3	6.6	80.0	85.0 b	83.0
Ilona	674	992 ab	---	0.02	0.03	---	1.58	1.96	---	10.7	10.0	---	84.5	82.8 b	---
Viola	653	969 ab	1042	0.02	0.02	0.04	1.72	2.24	1.80	9.0	10.1	7.2	85.5	94.3 ab	85.5
m.s.d.	-	211	-	-	-	-	-	-	-	-	-	-	-	11.6	-
Significance															
Cultivar	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	NS
C.V.	13.9	7.5	10.1	2.2	1.8	10.5	3.3	6.4	5.8	19.5	9.0	8.0	7.1	8.9	8.5

SA – St. Amable sandy loam site; SR – Ste. Rosalie clay site; BB – Bearbrook clay site
a, b Values within a column followed by the same letter(s) do not differ, according to Tukey's HSD test, $P \geq 0.05$
m.s.d. Minimum significant difference
*, ** Significant at $P < 0.05$, $P < 0.01$ levels of probability, respectively.
NS Not significant
C.V. Coefficient of variation

Table 2.4. Phenological development of ten fibre flax cultivars at the Macdonald site in 1998.

Cultivar	Days to emergence	Days to flowering	Days to harvest
Hermes	6	54	84
Evelin	6	48	79
Escalina	5	55	84
Viola	7	54	84
Diane	6	55	84
Viking	6	48	79
Belinka	7	50	82
Raisa	6	56	84
Ariane	6	55	84
Argos	5	55	84
Mean	6.0	53	82.8

Table 2.5A. Mean fresh weight and dry matter content for the various fibre flax cultivars at three locations in 1998.

	Mean fresh weight (t ha^{-1})			Mean dry matter content (%)[a]		
Cultivar	M	W	K	M	W	K
Hermes	18.1 ab	15.8 bc	19.1	42 abc	39 ab	40 ab
Evelin	15.2 b	----	19.8	46 a	----	38 b
Escalina	21.4 ab	19.5 abc	17.5	41 bc	39 ab	41 ab
Viola	19.0 ab	----	20.0	41 bc	----	41 ab
Diane	19.3 ab	26.0 a	20.7	41 bc	35 b	41 ab
Viking	16.9 ab	13.6 c	17.8	45 ab	44 a	43 a
Belinka	16.8 ab	20.5 abc	17.3	42 abc	40 ab	43 a
Raisa	20.8 ab	22.9 ab	19.9	39 c	34 b	43 a
Ariane	21.9 a	22.3 ab	21.9	38 c	35 b	41 ab
Argos	21.6 a	19.0 abc	21.3	39 c	37 ab	40 ab
m.s.d.	6.2	----	----	----	----	----
Significance						
Cultivar	**	***	NS	***	***	**
C.V.	13.5	13.4	18.5	4.6	7.1	3.7

M – Macdonald site; W – Winchester site; K – Kemptville site.
a, b, c Values within a column followed by the same letter(s) do not differ, according to Tukey's HSD test, $P \geq 0.05$.
m.s.d. Minimum significant difference.
, * Significant at $P < 0.01$, $P < 0.011$ levels of probability, respectively.
NS Not significant.
C.V. Coefficient of variation.
[a] Comparison of means performed on raw dry weight data but percent dry matter content data are presented.

Table 2.5B. Comparison of plant density, branching ratio, and stem diameter means for the fibre flax cultivar trials at three sites in 1998.

	Mean plant density (m^2)			Mean branching ratio			Mean stem diameter (mm)		
Cultivar	M	W	K	M	W	K	M	W	K
Hermes	1608 b	1322 ab	1590 ab	0.02 b	----	0.01 b	1.87 ab	1.67	1.51 b
Evelin	1808 ab	----	1565 ab	0.02 b	----	0.03 b	1.58 b	----	1.74 ab
Escalina	1800 ab	1289 ab	1375 ab	0.01 b	----	0.03 b	1.79 ab	1.47	1.79 ab
Viola	1850 ab	----	1440 ab	0.03 b	----	0.02 b	1.74 b	----	1.96 a
Diane	1592 b	1744 ab	1460 ab	0.04 b	----	0.03 b	1.77 b	1.71	1.65 ab
Viking	2325 a	1878 a	1665 a	0.02 b	----	0.02 ab	1.56 b	1.44	1.65 ab
Belinka	967 c	900 b	1170 b	0.15 a	----	0.08 a	2.22 a	1.66	1.74 ab
Raisa	2063 ab	1344 ab	1165 b	0.03 b	----	0.01 b	1.79 b	1.74	1.65 ab
Ariane	1850 ab	1689 ab	1575 ab	0.01 b	----	0.01 b	1.70 b	1.62	1.63 ab
Argos	1800 ab	1100 ab	1455 ab	0.01 b	----	0.01 b	1.75 b	1.69	1.79 ab
m.s.d.	581.3	899.4	12.4	0.06	----	0.05	0.37	----	0.36
Significance									
Cultivar	***	*	**	***	----	***	***	NS	*
C.V.	10.0	11.0	10.4	3.2	----	1.4	8.6	11.5	8.6

M – Macdonald site; W – Winchester site; K – Kemptville site.

a, b, c Values within a column followed by the same letter(s) do not differ, according to Tukey's HSD test, $P \geq 0.05$.

m.s.d. Minimum significant difference.

*, **, *** Significant at $P < 0.05$, $P < 0.01$ and $P < 0.001$ levels of probability, respectively.

NS Not significant.

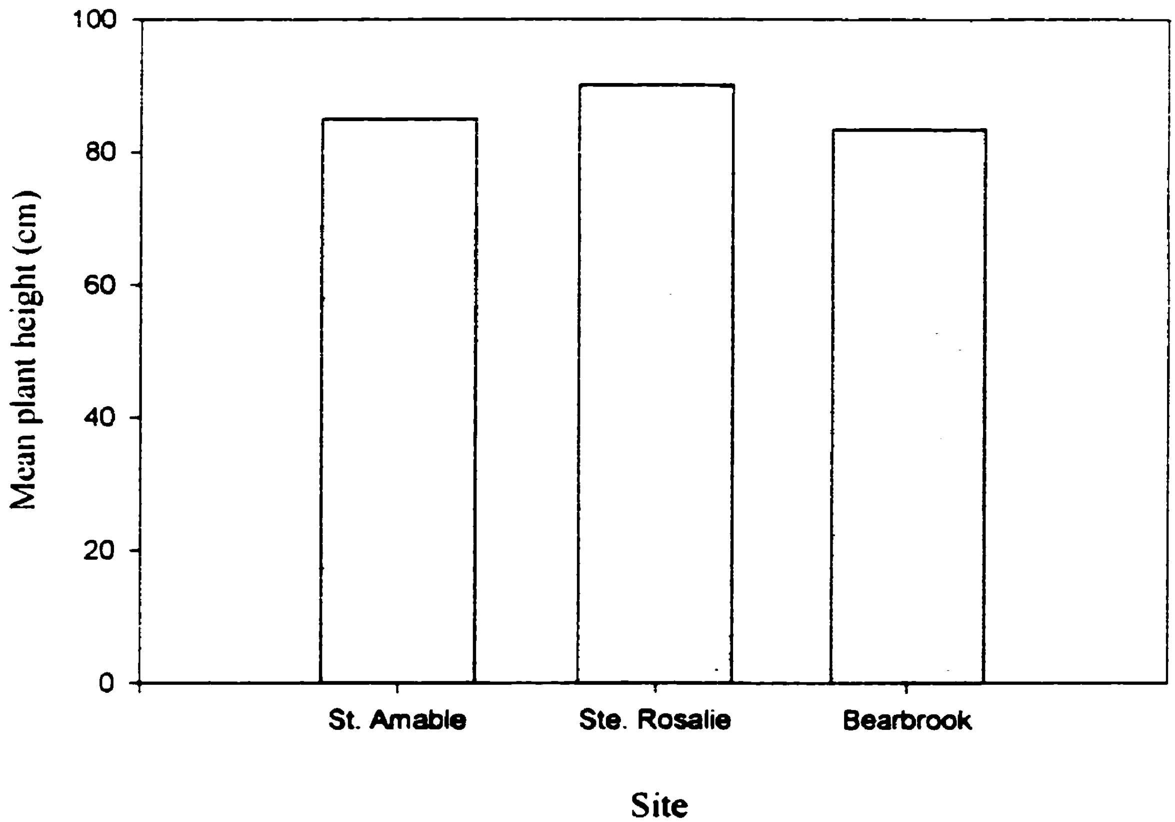
C.V. Coefficient of variation.

Table 2.5C. Mean plant heights at three sampling dates for various fibre flax cultivars at three locations in 1998.

	Height1 (cm)			Height2 (cm)			Height3 (cm)		
Cultivar	M	W	K	M	W	K	M	W	K
Hermes	16.2 de	6.7 d	----	66.3 ab	50.2 cd	52.5 abc	77.5 bcd	86.5 bc	96.0 bcd
Evelin	18.7 abcd	----	----	62.4 bc	----	46.8 c	70.2 e	----	94.0 cd
Escalina	13.6 e	7.0 cd	----	63.1 bc	45.8 d	48.5 c	83.3 a	89.8 ab	100.8 ab
Viola	16.1 de	----	----	64.2 bc	----	55.3 abc	76.4 cd	----	96.5 bc
Diane	19.9 ab	9.9 a	----	67.3 ab	61.9 a	60.3 ab	82.6 cd	96.4 a	104.3 a
Viking	21.3 a	7.8 bc	----	67.7 ab	56.3 abc	59.8 ab	73.9 de	79.1 c	91.5 cde
Belinka	19.9 ab	9.6 a	----	71.3 a	58.1 ab	61.0 a	82.2 ab	86.6 bc	100.5 ab
Raisa	16.6 cd	8.0 bc	----	60.0 c	52.8 bcd	55.3 abc	81.6 abc	89.3 ab	87.5 e
Ariane	17.9 bcd	8.9 ab	----	65.1 bc	52.4 bcd	45.0 c	81.7 ab	92.4 ab	95.5 bcd
Argos	19.1 abc	9.3 a	----	67.1 ab	54.8 abc	49.8 bc	81.8 ab	91.8 ab	90.5 de
m.s.d.	2.8	1.2	----	5.4	7.8	11.0	5.2	9.6	5.9
Significance									
Cultivar	***	***	----	***	***	***	***	***	***
C.V.	13.7	10.8	----	7.3	11.4	8.5	5.9	8.5	2.6

M – Macdonald site; W – Winchester site; K – Kemptville site.
Height1, Height2, Height3 Mean plant heights at four, six, and eight weeks post-emergence, respectively.
a, b, c, d, e Values within a column followed by the same letter(s) do not differ, according to Tukey's HSD test, P = 0.05
m.s.d. Minimum significant difference
*** Significant at $P < 0.001$.
NS Not significant.
C.V. Coefficient of variation.

Figure 2.1. Comparison of mean fibre flax height between three sites at Macdonald Campus in 1997, across cultivars.



100
80
60
40
20
0
Mean plant height (cm)
St. Amable
Ste. Rosalie
Bearbrook
Site

Figure 2.2. Comparison of mean fibre flax density between three sites at Macdonald Campus in 1997, across cultivars.

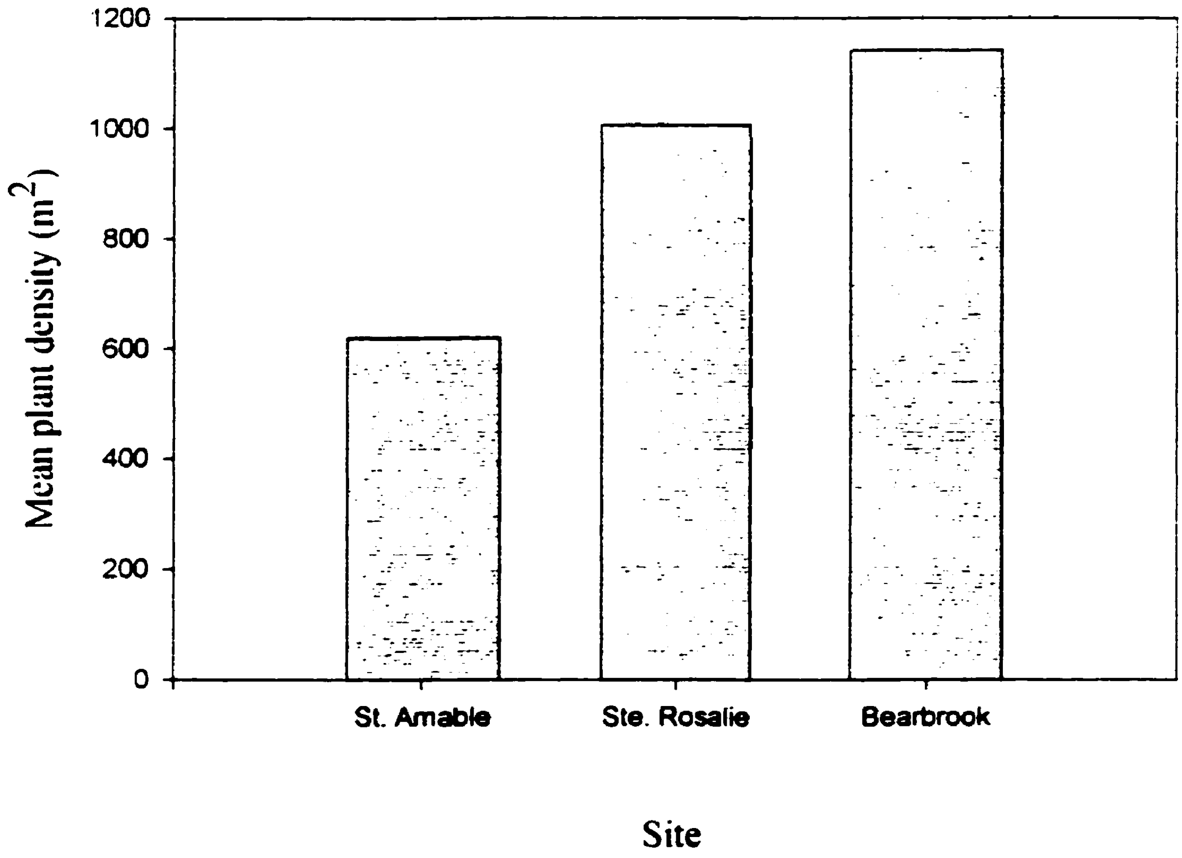
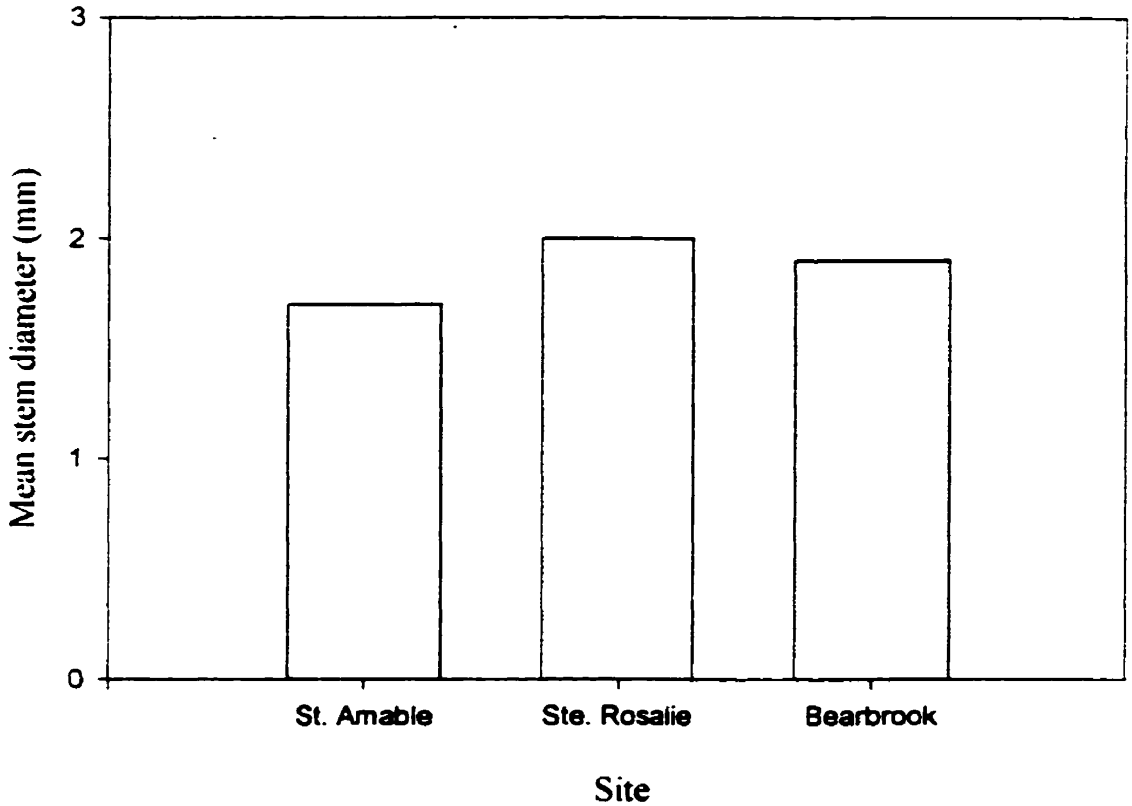
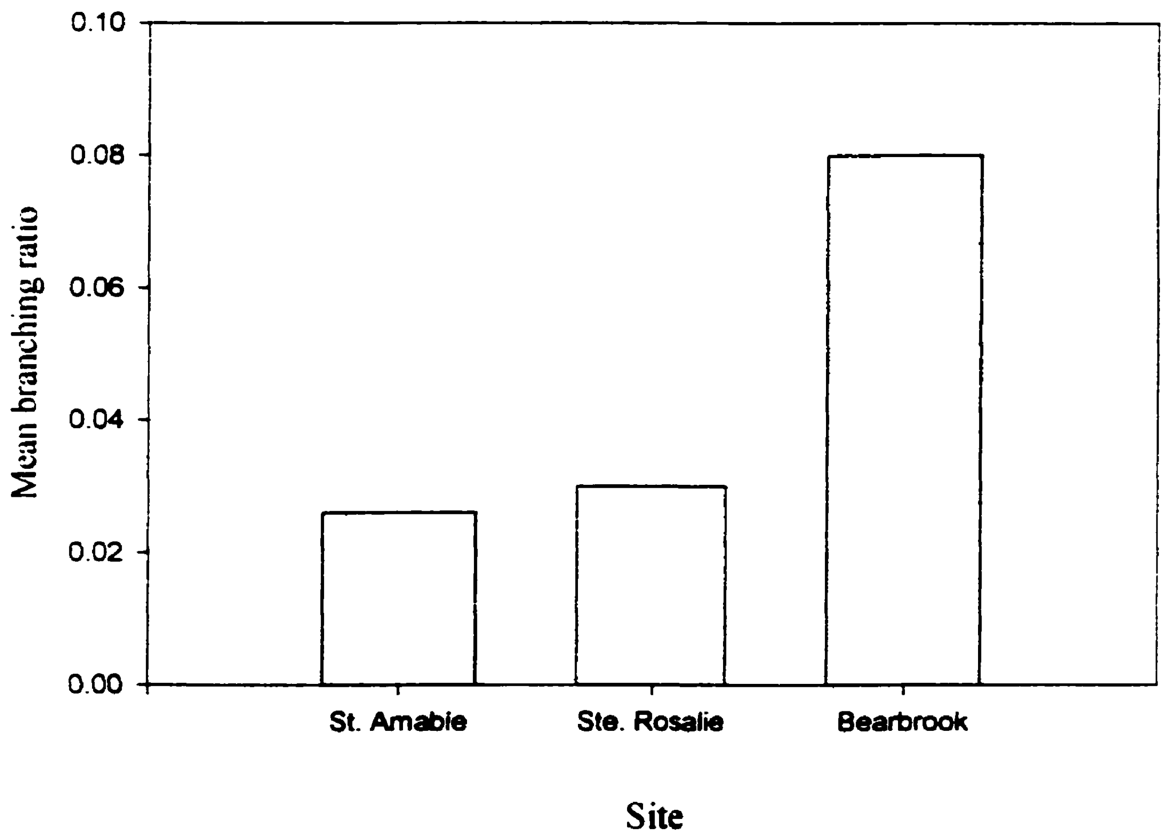

1200
1000
800
600
400
200
0
Mean plant density (m^2)
St. Amable
Ste. Rosalie
Bearbrook
Site

Figure 2.3. Comparison of mean fibre flax stem diameter between three sites at Macdonald Campus in 1997, across cultivars.



Mean stem diameter (mm)
3
2
1
0
St. Amable
Ste. Rosalie
Bearbrook
Site

Figure 2.4. Comparison of mean fibre flax branching ratio between three sites at Macdonald Campus in 1997, across cultivars.


0.10
0.08
0.06
0.04
0.02
0.00
Mean branching ratio
St. Amabie
Ste. Rosalie
Bearbrook
Site

Connecting Text

Evidence is presented in the previous chapter that fibre flax cultivars of European Origin can be successfully grown in Southern Québec and Eastern Ontario, Canada. Fundamental agronomic considerations such as seeding depth and soil packing prior to or following seeding, are important to the successful establishment of any crop, including fibre flax. The following chapter presents research conducted to determine an optimal seeding depth for fibre flax (cv. Ariane), and to ascertain the benefits of soil packing (rolling) prior to or after seeding versus no packing at all. Also of interest is any interaction that occurs between seeding depth and soil packing.

Chapter 3. Effects of Seeding Depth and Soil Compaction on Emergence and Yield Characteristics of Fibre Flax

3.1. Abstract

Research was conducted at Macdonald Campus of McGill University at three sites in 1997 and one site in 1998 to determine the effects and interactions of seeding depth (zero, one, two, four, or six cm) without soil compaction (rolling) or with rolling before and after seeding on fibre flax (cv. Ariane). Results indicate that rolling had little impact on any of the parameters assessed, while seeding depth had a variable effect on plant density, stem diameter, plant height and retted straw yield. Seeding depths of one to four centimeters provided consistently good results. In 1997, there was an interaction between seeding depth and rolling on branching ratio, plant height, and retted straw yield, although results were generally variable and tended to be site-specific. In 1998, there was an interaction between seeding depth and rolling on mean stem diameter and plant height prior to harvest, with the results varying for all depth-rolling treatment combinations except the two centimeter depth.

3.2. Introduction

Early and uniform establishment is paramount to the success of fibre flax crops for a number of reasons. Fibre flax is seeded at very high densities to attain optimal populations of 2000 plants m^2 (Sultana, 1983; Stephens, 1997), so even a partial delay in emergence can result in a highly non-uniform stand, as plants which emerged late will be at a competitive disadvantage (Fowler, 1984). Uniformity is a desirable characteristic in fibre flax destined for linen production, as the length of fibres will influence the price a producer obtains for the crop (Ulrich & Laugier, 1995).

Stand uniformity is affected by seedbed preparation as well as seed placement (Lafond et al., 1996). Seed placement plays a prominent role in the time to emergence of flax and may have an impact on seedling vigour. Sultana (1983) reported an optimal depth of two centimeters for the sowing of fibre flax. The results of a study by O'Connor & Gusta (1994) on oilseed flax suggested that flax sown at a depth of four centimeters takes 33% longer to emerge than flax sown at a depth of two centimeters, and that overall emergence is lower from a depth of four centimeters. Another study by Wall (1994) suggests reductions of up to 59% in oilseed flax populations when seeded at a depth of six centimeters compared to with a depth of three centimeters. One practice commonly used to help improve emergence is compacting or rolling the soil before or after seeding to improve seed to soil contact, and seedbed firmness. This practice is also likely to impact emergence and early growth patterns of a given crop species (Lafond et al., 1996). Compacting the soil after seeding is a practice frequently employed in forage production, to help improve seed to soil contact (Barnes et al., 1995).

The results of a study in Québec suggest that soil preparation and seeding depth are extremely important in fibre flax production (Robert, 1998). Seeds placed too deep in the soil emerge in an uneven manner, leading to uneven development and a high proportion of immature plants during harvesting. The same study indicated rolling the soil prior to seeding operations may have a beneficial effect (Robert, 1998).

Research was conducted at Macdonald Campus of McGill University in 1997 and 1998 to examine the potential effects and interactions of depth of seeding with soil compaction (rolling) prior to vs. after seeding, or not at all, on fibre flax (cv. Ariane) in a conventional tillage system.

3.3. Materials and methods

The research was conducted in 1997 and 1998 at Macdonald Campus, McGill University, in Ste. Anne-de-Bellevue, Québec, Canada. There were three experimental sites at the Macdonald Campus in 1997, and only one site in 1998. The first site was located on a St. Amable loamy sand soil (well drained, Gleyified Humo Ferric Podzol; pH 5.0-5.7) (Lajoie, 1960), the second site was located on a Macdonald clay loam soil (poorly drained, Dark Gray Gleysolic; pH5.8-6.2) (Lajoie, 1960), and the third site was located on a Bearbrook clay soil (poorly drained, Dark Gray Gleysolic; pH 5.6-6.4) (Lajoie, 1960). Previous crops in each location were soybean in 1996 at the St. Amable site, and fallow in 1995. The Macdonald clay loam and Bearbrook clay sites were both sown to wheat in 1996, and corn in 1995. The single site in 1998 was located on a St. Bernard loam soil (well drained, Melanic Brunisol, pH 6.07) (Lajoie, 1960), the prior crops being barley in 1997, and red clover in 1996 and 1995.

Land preparation in both years consisted of fall moldboard plowing followed by spring disking and harrowing prior to seeding. In both years, 200 kg ha $^{-1}$ of balanced fertilizer (20-10-10) was incorporated prior to seeding.

The cultivar 'Ariane' was seeded at the rates of 100 (1997) and 125 (1998) kg ha $^{-1}$ using a five row Bolens drill seeder having a row spacing of 20cm, at manually controlled depths of zero, one, two, four, and six centimeters. Seeding occurred on May 25 in 1997 and April 30 in 1998 into 2 m x 5.5 m plots. The experimental design was a strip-plot design in which the strips (vertical factor) were seeding depth, and the blocks (horizontal factor) were one of three treatments: a) rolling prior to seeding (RB), b) rolling after seeding (RA), or c) no rolling (NR). There were three blocks, with one replicate/treatment/block. Field layouts in all sites in both years were identical.

Weed infestation necessitated spraying in both years. In 1997, the Macdonald clay loam site was sprayed with sethoxydim (Poast®) + mineral oil surfactant (0.276 kg ai ha^{-1} + 2 L ha^{-1}) for control of annual grasses. The St. Amable and Bearbrook clay sites were sprayed with bentazon (Basagran Forte®) at a rate of 0.960 kg ai ha^{-1} for the control of broadleaf weeds and yellow nutsedge (*Cyperus esculentus* L.). The 1998 site was sprayed with fluazifop-p-butyl (Venture®) + mineral oil surfactant (0.7 kg ai ha^{-1} + 0.5 % v/v) for annual grass and quackgrass (*Elytrigia repens* (L.) Nevski) control. Later in the season, bentazon (Basagran Forte®) was applied (1.08 kg ai ha^{-1}) to control emerged annual broadleaf weeds. All herbicide treatments followed recommendations for oilseed flax in Publication 75: Guide to Weed Control (Anon., 1997).

Climatological data (temperature, rainfall, and growing degree days) for both years were recorded by an automatic weather station at the Agronomy Centre of Macdonald Campus. These data are presented in Appendix 2.1.

3.3.1. Data Collection

The data collected from all experiments aimed to assess the effects of seeding depth and soil compaction on the emergence pattern of fibre flax. Of additional interest were the yield and quality of fibres produced within the various treatments. Fibre quantity and quality were to be assessed by professionals at the Gilflax Inc. flax scutching mill in Valleyfield, Québec, Canada.

3.3.1.2. 1997 Growing season

Data collection in 1997 included average plant height (measured from soil level to the uppermost growing point) per plot, and was recorded prior to harvest. The plot average was the mean of two observations where a group of plants (approximately 8-12) were held together against a meter-stick, and their average heights estimated as one value.

Plant densities in each plot were assessed twice within a 30 cm x 30 cm quadrat. Within each of these quadrats, the number of plants that had branches within the first 50 cm of stem were also counted. The number of plants with branches was divided by the number of plants in each sample, resulting in a "branching ratio" referred to as Tratio, following a square root + 1 transformation to satisfy the normality requirement of ANOVA (Gomez & Gomez, 1984). This transformation was also done on the plant density data.

"Retted" straw yield was also assessed (refer to Chapter 1 for explanation of the retting process). The area harvested per plot in 1997 was large at one meter by five meters, since the sample size required by the scutching mill for quality analysis was unknown. The plants were uprooted by hand when at least two thirds of the leaves had been shed, and capsules were beginning to turn brown in colour (Stephens, 1997). The soil was shaken from the roots, and the plants were then laid in the field for approximately two weeks, after which they were turned over by hand, and were left in the field for approximately ten days more while the retting process continued. The retted plot yield was then recorded and bulked by treatment, for transportation to the scutching mill.

3.3.1.3. 1998 Growing season

Data collection in 1998 was similar to that in 1997 with a few important differences. A variety of phenological parameters were assessed and included counting the number of days to emergence, flowering and harvest.

Due in part to the subjectivity involved in assessing the degree of retting for each treatment independently, and to the closure of the Gilflax Inc. scutching mill, fresh and dry weights were obtained since fibre quantity and quality could not be assessed.

Plant densities were measured twice within a 25 cm x 12 cm strip of each plot, and branching ratios were calculated as in 1997. Stem diameter data were assessed on 25 randomly selected plants per plot using a Marathon 150mm electronic digital caliper (Marathon Management Co., Richmond Hill, Ont.), and plot means were used in the data analysis. Average plant heights were measured using the same procedure as in 1997, except that six measurements were recorded per plot rather than two, and three sampling dates used (three, six, and nine weeks post emergence) rather than one.

All data collected were subjected to analysis of variance (ANOVA) using the GLM procedure in SAS (SAS Institute, Inc., 1985), to identify main effects and interactions of seeding depth with rolling, on the various parameters measured. Significant results ($P<0.05$) were then subjected to a Tukey's HSD means comparison procedure (Motulsky, 1995) to identify differences between specific treatments.

3.5. Results

3.5.1. 1997 Field trials

The growing season in 1997 was much wetter than usual, with only the month of June having normal precipitation levels (Appendix 2.1). Temperatures were below normal in April and May, and normal for the rest of the season (Appendix 2.1). The season long number of growing degree days (base of 5° C) was lower by 150 compared with the average (Appendix 2.1).

The effect of rolling was not significant ($P \geq 0.05$) at the Bearbrook site (Appendix 3.1). There was however, a significant ($P < 0.05$) effect of seeding depth on plant density and a highly significant ($P < 0.001$) effect on retted straw yield (Appendix 3.1). The six centimeter seeding depth resulted in the greatest plant densities, whereas the zero centimeter seeding depth resulted in the lowest plant densities (Table 3.1). Seeding depths of one, two and six centimeters resulted in yields greater than 5 t ha $^{-1}$ of retted straw, just under 4 t ha $^{-1}$ for the four centimeter depth, and 1.7 t ha $^{-1}$ for the zero centimeter treatment plots (Table 3.1). There was also a highly significant ($P < 0.001$) interaction between rolling and seeding depth on retted straw yield (Appendix 3.1). The highest yielding combination (6.1 t ha $^{-1}$) was at a depth of one centimeter with no rolling, while the zero centimeter seeding depth treatment plots rolled prior to seeding resulted in no yield (Table 3.2).

Results from the St. Amable site were similar to those obtained at the Bearbrook clay site in that there was no main effect of rolling observed on any of the parameters measured (Appendix 3.2). Seeding depth had a significant ($P < 0.05$) effect on plant density and retted weight (Appendix 3.2). The one centimeter depth treatment resulted in the highest plant density (272 plants m^2), as well as the highest yield of retted straw (7.2 t ha $^{-1}$) (Table 3.3). In contrast, the six centimeter depth resulted in the lowest plant density (129 plants m^2), as well as the lowest yield of retted straw (4.0 t ha $^{-1}$) (Table 3.3). There was also a significant ($P < 0.05$) interaction between rolling and seeding depth on branching ratio and retted straw yield (Appendix 3.2). The combination of zero centimeters seeding depth and rolling prior to seeding resulted in the highest proportion of branched plants, 0.46 or 46% (Table 3.4). The combination of one centimeter seeding depth and rolling prior to seeding yielded the most retted straw, 8.3 t ha^{-1} (Table 3.4), while depths of four and six centimeters rolled after seeding yielded only 2.7 and 3.0 t ha^{-1} of retted straw, respectively (Table 3.4.).

At the Macdonald clay loam site, rolling had a significant ($P < 0.05$) effect only on plant height (Appendix 3.3). Rolling prior to seeding resulted in an overall increase in mean height of approximately seven centimeters, compared with the other rolling treatments (Table 3.5). Seeding depth had a significant ($P < 0.05$) effect on branching ratio (Appendix 3.3), with three times as many plants in the zero centimeter depth plots having branches than the plants in the two centimeter depth plots (Table 3.5). There were highly significant ($P < 0.01$) interactions between seeding depth and rolling on branching ratio, retted straw yield, and mean plant height (Appendix 3.3). The plots with the highest branching ratio were the zero centimeter plots rolled prior to seeding (Table 3.6). None of the other treatment combinations differed significantly ($P \geq 0.05$) in branching ratio from one another (Table 3.6). The treatment combination of zero centimeters seeding depth rolled prior to seeding resulted in the lowest yield of retted straw, only 1.5 t ha^{-1} (Table 3.6). The tallest plants, with a mean height of 81 cm, were found in the four centimeter non-rolled treatment combination plots, while the shortest plants (63.7 cm) were found in the six centimeter plots rolled prior to seeding (Table 3.6).

3.5.2. 1998 Field trials

The month of April in 1998 was considerably warmer and drier than usual (Appendix 2.1). The mean temperature was 2° C above normal, with only a quarter of the normal rainfall, thus allowing seeding to take place relatively early (Appendix 2.1). In fact, temperatures were above normal every month from April to September, except for July, which was one degree below normal (Appendix 2.1). The same pattern stood for rainfall, with every month below normal, except for June, which had 1.5 times the normal rainfall (Appendix 2.1). The number of growing degree days (base of 5° C) was correspondingly higher than normal (Appendix 2.1).

Emergence was faster in plots seeded at depths of one or two centimeters, and the slowest in the six centimeter depth treatment plots (Table 3.7A). Emergence was accelerated in plots rolled prior to seeding, followed by plots without rolling, and plots rolled after seeding (Table 3.7B). There was little difference as to length of time to flowering or harvest between the rolling treatments or seeding depth treatments (Tables 3.7A & B). The one and two centimeter plots without rolling or rolled prior to seeding hastened emergence (mean of 4.5 days) when compared with the four and six centimeter depths rolled after seeding or not at all (mean of 10.8 days) (Table 3.7B).

There were no significant ($P \geq 0.05$) effects due to rolling on any of the parameters measured (Appendix 3.4). Seeding depth had a significant ($P < 0.05$) effect on stem diameter and mean plant height three weeks post-emergence, and a highly significant effect ($P < 0.01$) on mean plant height nine weeks post-emergence (Appendix 3.4). Stem diameters were the highest in the zero centimeter depth treatment plots, and were lowest in the two centimeter depth treatment plots (Table 3.8). At three weeks post-emergence, plants in the one centimeter depth plots averaged 17.5 cm in height compared with 14.5 cm for plants in the zero centimeter depth plots (Table 3.8). However, by nine weeks post-emergence, plants in the zero centimeter depth plots were tallest, averaging 90.4 cm in height, compared with 86.5 cm for plants in the one centimeter depth plots (Table 3.8).

There was a highly significant ($P < 0.01$) interaction between rolling regime and seeding depth on stem diameter and mean plant height at nine weeks post-emergence (Appendix 3.4). Stem diameters were highest for plants in plots which were seeded at a depth of six centimeters and rolled after seeding, as well as for plants in the zero centimeter depth treatment rolled prior to seeding (Table 3.9A). Stem diameters were thinnest for plants in the one and two centimeter depth plots rolled after seeding, and for the two centimeter depth plots either rolled prior to seeding or not rolled at all (Table 3.9A). Overall, plants within the zero centimeter depth plots with no rolling were the tallest plants (92.4 cm) while plants within the two centimeter depth treatment plots rolled prior to seeding were shortest (84.4 cm) (Table 3.9B).

3.6. Discussion

Seed to soil contact is essential in any agricultural production system to obtain high levels of germination and emergence (Waddington, 1992; Stephens & Johnson, 1993; Lafond et al., 1996). Our results consistently indicated no main effect of rolling on any of the parameters measured at any site in either year, with the exception of plant height at the Macdonald clay loam site in 1997. However, in a number of cases, rolling did interact with seeding depth, but no clear trend emerged. Despite a lack of significant results, rolling after seeding generally resulted in higher plant populations in lighter soils, and reduced plant populations in heavier soils. This finding was not statistically tested due to significant within site-variability determined using Bartlett's test (Gomez & Gomez, 1984). In a recent Québec study, Robert (1998) observed beneficial effects due to rolling prior to seeding, unfortunately in this study there was no rolling after seeding treatment with which to compare results. Robert (1998) also noted that when the seedbed was too soft, the depth of seeding tended to be greater, leading to reduced seedling emergence. Under these conditions rolling prior to seeding may be useful.

Seeding depth is considered to be a major factor in crop establishment (O'Connor & Gusta, 1994), and our results support this view. A seeding depth of two centimeters has been suggested by Sultana (1983) to be optimal, while seeding depths greater than four centimeters can lead to substantially lower fibre flax populations (Robert, 1998). In our trials, a seeding depth of two centimeters typically resulted in an average to above average flax population density, mean plant height and yield, and a lower proportion of branched plants, with finer stems. Nonetheless, depths of one and four centimeters did provide acceptable results. These parameters are considered important for fibre flax production (Robinson, 1933; Hocking et al., 1987; Maiti, 1997), when the fibres are destined for linen production.

In neither year did plant densities approached the desirable level of 1800-2000 plants m^2 (Lockhart & Wiseman, 1988) in 1997. Increasing the seeding rate in 1998 by 25 kg ha^{-1} helped, but flax populations remained approximately half of the desired level. Results of a study in Québec also indicated a degree of difficulty in achieving appropriate population densities (Robert, 1998). Low seeding rate, poor seedbed preparation and mechanical difficulties with seeding equipment were all cited as likely causes for the suboptimal plant populations obtained (Robert, 1997; 1998). Although retted straw yields in 1997 appear excessively high relative to the plant populations present, extremely high rates of branching and increased plant stem diameters might account for this finding. Branching ratios were much reduced in 1998, likely due to the higher seeding rate and increased intra-specific competition amongst plants (Hocking et aL, 1987). Contrary to findings by Rowland (1980), plant height was not adversely affected by an increase in plant population (due to increased seeding rate) in 1998. In fact mean plant height actually seemed to increase.

In conclusion, the impact of rolling the soil and seeding depth may largely depend on soil type and the specific type of production system in use. Our results demonstrated that rolling may be beneficial prior to seeding on lighter soils, a finding that is consistent with observations by Robert (1998). The extra costs associated with rolling the soil at any given time may not immediately appear to be worthwhile, however all indications suggest that rolling is not likely to be detrimental to the crop. Moreover, a finding consistent with Sultana (1983) suggests a fibre flax seeding depth of two centimeters appears to be an effective target depth for a wide range of Québec soil and climatic conditions.

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Table 3.1. Mean values for various fibre flax plant production parameters as affected by sowing depth and soil packing at the Bearbrook clay site in 1997.

Treatment	Mean plant density (plants m²)	Mean branching ratio %	Mean retted straw yield (t ha $^{-1}$)	Mean plant height (cm)
Depth (cm)				
0	188 b	0.22	1.7 c	73.8
1	319 a	0.13	5.2 a	76.7
2	254 ab	0.22	5.5 a	79.3
4	235 ab	0.12	4.0 b	74.6
6	337 a	0.11	5.1 a	75.3
m.s.d.	111	-	0.9	-
Rolling				
NR	285	15.7	3.8	78.0
RA	267	13.5	4.7	76.1
RB	247	19.4	4.3	73.7
m.s.d.	-	-	-	-

a, b, Values within a column followed by the same letters do not differ, according to Tukey's HSD test, $P \geq 0.05$.
NR No rolling.
RA Rolled after seeding.
RB Rolled before seeding.
m.s.d. Minimum significant difference.

Table 3.2. Comparison of means for all seeding depth-rolling treatment combinations at the Bearbrook clay site in 1997, based on significant ANOVA interaction results.

Treatment	Mean plant density (m^2)	Mean branching ratio	Mean retted straw yield ($t\ ha^{-1}$)	Mean plant height (cm)
Not rolled				
0 cm	119	0.28	2.2 cd	73.3
1 cm	391	0.12	6.1 a	78.7
2 cm	263	0.19	5.7 ab	79.7
4 cm	243	0.09	4.0 abc	71.7
6 cm	409	0.10	5.3 ab	77.0
Rolled after				
0 cm	228	0.19	2.8 bcd	77.7
1 cm	302	0.16	4.6 abc	77.0
2 cm	281	0.10	5.6 ab	83.7
4 cm	250	0.11	4.0 abc	78.7
6 cm	276	0.12	4.6 abc	73.0
Rolled before				
0 cm	217	0.19	0 d	70.3
1 cm	265	0.12	4.8 abc	74.3
2 cm	219	0.36	5.2 abc	74.7
4 cm	211	0.18	3.9 abc	73.3
6 cm	326	0.12	5.3 ab	76.0
m.s.d.	-	-	3.1	-

a, b, c, d Values within a column followed by the same letters do not differ, according to Tukey's HSD test, $P \geq 0.05$.
NR No rolling.
RA Rolled after seeding.
RB Rolled before seeding.
m.s.d. Minimum significant difference.

Table 3.3. Mean values for various fibre flax production parameters as affected by sowing depth and soil packing at the St. Amable sandy loam site in 1997.

Treatment	Mean plant density (plants m²)	Mean branching ratio	Mean retted straw yield (t ha $^{-1}$)	Mean plant height (cm)
Depth (cm)				
0	234 ab	0.24	5.2 bc	88.0
1	272 a	0.14	7.2 a	88.8
2	222 ab	0.13	6.2 ab	90.9
4	189 ab	0.09	5.1 bc	88.6
6	129 b	0.17	4.0 c	87.8
m.s.d.	106	-	1.5	-
Rolling				
NR	191	12.5	5.6	89.4
RA	203	12.9	4.7	87.6
RB	234	20.2	6.4	89.5
m.s.d.	-	-	-	-

a, b, c Values within a column followed by the same letters do not differ, according to Tukey's HSD test, $P \geq 0.05$.
NR No rolling.
RA Rolled after seeding.
RB Rolled before seeding.
m.s.d. Minimum significant difference.

Table 3.4. Comparison of means for all seeding depth-rolling treatment combinations for the St. Amable sandy loam site in 1997, based on significant ANOVA interaction results.

Treatment	Mean plant density (m^2)	Mean branching ratio	Mean retted straw yield (t ha^{-1})	Mean plant height (cm)
Not rolled				
0 cm	202	0.17 ab	5.7 ab	88.0
1 cm	213	0.15 ab	6.7 ab	90.7
2 cm	196	0.15 ab	5.8 ab	92.0
4 cm	164	0.03 b	5.8 ab	87.0
6 cm	178	0.13 ab	3.8 ab	89.7
Rolled after				
0 cm	280	0.09 b	5.8 ab	87.7
1 cm	252	0.21 ab	6.5 ab	92.0
2 cm	220	0.07 b	5.4 ab	92.0
4 cm	189	0.14 ab	3.0 b	88.7
6 cm	74	0.12 ab	2.7 b	86.7
Rolled before				
0 cm	220	0.46 a	4.2 ab	88.3
1 cm	352	0.05 b	8.3 a	83.3
2 cm	250	0.16 ab	7.5 ab	88.7
4 cm	213	0.09 b	6.1 ab	90.0
6 cm	135	0.25 ab	5.5 ab	87.0
m.s.d.	-	0.36	5.1	-

a, b Values within a column followed by the same letters do not differ, according to Tukey's HSD test, $P \geq 0.05$.
NR No rolling.
RA Rolled after seeding.
RB Rolled before seeding.
m.s.d. Minimum significant difference.

Table 3.5. Mean values for various fibre flax production parameters as affected by sowing depth and soil packing at the Macdonald clay loam site in 1997, based on significant ANOVA results.

Treatment	Mean plant density (plants m^2)	Mean branching ratio	Mean retted straw yield (t ha^{-1})	Mean plant height (cm)
Depth (cm)				
0	291	0.32 a	4.3	73.4
1	367	0.18 ab	5.4	71.9
2	425	0.10 b	4.6	75.3
4	376	0.17 ab	5.4	72.8
6	371	0.13 ab	5.6	73.2
m.s.d.	-	0.19	-	-
Rolling				
NR	307	0.15	5.2	71.3 b
RA	407	0.16	5.0	70.9 b
RB	383	0.22	5.0	77.8 a
m.s.d.	-	-	-	3.7

a, b Values within a column followed by the same letters do not differ, according to Tukey's HSD test, $P \geq 0.05$.
NR No rolling.
RA Rolled after seeding.
RB Rolled before seeding.
m.s.d. Minimum significant difference.

Table 3.6. Comparison of means for all seeding depth-rolling treatment combinations for the Macdonald clay loam site in 1997, based on significant ANOVA interaction results.

Treatment	Mean plant density (m^2)	Mean branching ratio	Mean retted straw yield (t ha^{-1})	Mean plant height (cm)
Not rolled				
0 cm	337	0.14 b	5.7 a	75.0 abc
1 cm	222	0.25 b	5.7 a	75.0 abc
2 cm	339	0.12 b	3.3 ab	78.3 ab
4 cm	350	0.12 b	5.3 a	81.0 a
6 cm	289	0.13 b	5.9 a	79.7 ab
Rolled after				
0 cm	306	0.18 b	5.8 a	73.3 abcd
1 cm	472	0.11 b	5.1 ab	67.3 cd
2 cm	411	0.09 b	4.9 ab	72.7 abcd
4 cm	389	0.23 b	4.6 ab	67.0 cd
6 cm	457	0.19 b	4.6 ab	76.3 abc
Rolled before				
0 cm	230	0.62 a	1.5 b	72.0 abcd
1 cm	406	0.17 b	5.4 ab	73.3 abcd
2 cm	524	0.10 b	5.5 a	75.0 abc
4 cm	389	0.15 b	6.3 a	70.3 bcd
6 cm	367	0.07 b	6.2 a	63.7 d
m.s.d.	-	0.34	3.7	10.2

a, b, c, d Values within a column followed by the same letters do not differ, according to Tukey's HSD test, $P \geq 0.05$.
NR No rolling.
RA Rolled after seeding.
RB Rolled before seeding.
m.s.d. Minimum significant difference.

Table 3.7A. Phenological development of fibre flax plants in 1998 as affected by seeding depth and soil packing).

Treatment	Mean number of days to emergence	Mean number of days to flowering	Mean number of days to harvest
Seeding depth			
0 cm	9	56.7	81.7
1 cm	6	53	84
2 cm	6	53	84
4 cm	9	53	84
6 cm	10.3	53	84
Rolling			
RB	6.2	54	83.6
RA	10	53.4	83.6
NR	8	53.8	83.4

RB Rolled before seeding.
RA Rolled after seeding.
NR No rolling.

Table 3.7B. Phenological development of fibre flax plants for all possible treatment combinations of sowing depth and soil packing.

Treatment	Days to emergence	Days to flowering	Days to harvest
0 cm, NR	10	57	81
1 cm, NR	5	53	84
2 cm, NR	5	53	84
4 cm, NR	10	53	84
6 cm, NR	10	53	84
0 cm, RA	9	55	82
1 cm, RA	9	53	84
2 cm, RA	9	53	84
4 cm, RA	11	53	84
6 cm, RA	12	53	84
0 cm, RB	8	58	82
1 cm, RB	4	53	84
2 cm, RB	4	53	84
4 cm, RB	6	53	84
6 cm, RB	9	53	84

NR No rolling.
RA Rolled after seeding.
RB Rolled before seeding.

Table 3.8. Means values for various fibre flax production parameters as affected by sowing depth and soil packing at Macdonald in 1998.

Treatment	Mean plant density (m^2)	Mean branching ratio	Mean stem diameter (mm)	Mean fresh straw yield (t ha^{-1})	Dry matter content (%)	Ht1 (cm)
Depth (cm)						
0	1020	0.081	2.87 a	29.3	34.7	14.5 b
1	1096	0.031	2.55 bc	28.5	36.0	17.5 a
2	998	0.044	2.42 c	26.9	35.7	16.5 a
4	1078	0.049	2.69 ab	28.5	36.9	16.8 a
6	957	0.067	2.78 ab	26.1	37.9	16.5 a
m.s.d.	-	0.042	0.24	-	-	1.6
Rolling						
NR	976	0.034	2.65	28.2	35.8	16.7
RA	1072	0.052	2.64	27.9	36.0	15.0
RB	1042	0.078	2.69	27.4	36.9	17.4
m.s.d.	-	-	-	-	-	-

NR No rolling.
RA Rolled after seeding.
RB Rolled before seeding.
a, b, c Values within a column followed by the same letters do not differ at $P \geq 0.05$, according to Tukey's HSD test.
m.s.d. Minimum significant difference.

Table 3.9A. Comparison of means for all sowing depth and rolling treatment combinations from the 1998 seeding depth trial, based on significant ANOVA interaction results.

Treatment	Mean stem diameter (mm)	Mean plant density (m^2)	Mean branching ratio	Mean fresh weight ($t\ ha^{-1}$)	Mean dry matter content (%)
Not rolled					
0 cm, NR	2.77 ab	928	0.078	28.5	34.2
1 cm, NR	2.70 ab	1022	0.016	30.8	33.3
2 cm, NR	2.42 b	994	0.021	30.3	34.5
4 cm, NR	2.74 ab	1056	0.026	27.1	38.3
6 cm, NR	2.62 ab	878	0.029	24.0	38.7
Rolled after					
0 cm, RA	2.75 ab	1006	0.094	32.8	34.8
1 cm, RA	2.44 b	1167	0.018	28.8	37.3
2 cm, RA	2.42 b	1017	0.031	24.2	35.3
4 cm, RA	2.74 ab	1089	0.049	28.9	34.7
6 cm, RA	3.12 a	1083	0.067	25.0	38.0
Rolled before					
0 cm, RB	3.10 a	1128	0.071	26.5	35.2
1 cm, RB	2.51 ab	1100	0.078	25.8	37.3
2 cm, RB	2.42 b	983	0.080	26.1	37.2
4 cm, RB	2.59 ab	1089	0.072	29.4	37.7
6 cm, RB	2.59 ab	911	0.106	29.4	37.0
m.s.d.	0.65	-	-	-	-

a, b Values within a column followed by the same letters do not differ, according to Tukey's HSD test, $P \geq 0.05$.
NR No rolling.
RA Rolled after seeding.
RB Rolled before seeding.
m.s.d. Minimum significant difference.

Table 3.9B. Comparison of plant height means for all seeding depth and rolling treatment combinations at the three sampling dates for the seeding depth trial in 1998, based on significant ANOVA results.

Treatment	Ht1 (cm)	Ht2 (cm)	Ht3 (cm)
0 cm, NR	14.8	73.4	92.4 a
1 cm, NR	17.7	78.8	86.3 abc
2 cm, NR	16.0	75.0	88.2 abc
4 cm, NR	18.1	72.6	85.8 bc
6 cm, NR	16.8	75.3	85.7 abc
0 cm, RA	14.5	71.6	88.2 abc
1 cm, RA	18.8	76.2	86.7 abc
2 cm, RA	17.8	76.0	87.1 abc
4 cm, RA	17.6	78.3	86.4 abc
6 cm, RA	18.1	75.3	88.3 abc
0 cm, RB	14.3	66.0	90.7 ab
1 cm, RB	16.2	75.3	86.6 abc
2 cm, RB	15.6	73.3	84.4 c
4 cm, RB	14.6	72.7	88.9 abc
6 cm, RB	14.5	74.2	86.8 abc
m.s.d.	-	-	6.1

a, b, c Values within a column followed by the same letters do not differ, according to Tukey's HSD test, $P \geq 0.05$.

Ht1, Ht2, Ht3 Plant heights three, six, and nine weeks post-emergence.

NR No rolling.

RA Rolled after seeding.

RB Rolled before seeding.

m.s.d. Minimum significant difference.

Connecting Text

Data presented in the preceding chapter suggest fibre flax should be seeded at a shallow depth of one to four centimeters, and that soil packing may or may not be beneficial, depending on the soil type. Seeding depth and soil packing are important components of crop establishment, and are also linked to seedbed preparation. The question arises of how fibre flax might perform in minimal or zero tillage systems which have been gaining popularity in recent years, and which tend to vary in seedbed fineness. The following chapter describes research conducted to evaluate the performance of fibre flax (cv. Ariane) in minimum and zero tillage systems, compared to a conventional tillage system.

Chapter 4. Evaluation of Fibre Flax Performance in Minimal and Zero Tillage Systems

4.1. Abstract

Research was initiated at two sites in 1998 at Macdonald Campus of McGill University, Ste. Anne-de-Bellevue, Québec, Canada to investigate the feasibility of producing fibre flax in minimum tillage or zero tillage systems. Results were inconsistent between the sites, which differed in soil type, and previous cropping history. The oat stubble site was on a Chicot fine sandy loam soil, and the soybean stubble site was on a Bearbrook clay soil. Tillage regime had no impact on fibre flax phenological development including number of days to emergence, days to flowering and days to harvest at either site. Tillage regime did, however, have a significant effect on mean stem diameter, dry matter content, and plant height at all three sampling dates at the oat site, and a significant effect on mid-season plant height at the soybean site. At the oat site, zero tillage plots had the highest population of plants with the finest stem diameter, the lowest branching ratio, but the shortest plants by the end of the season. Overall, plant densities were higher, stem diameters thinner, and biomass production higher in the heavier soil of the soybean site. These results indicate that fibre flax can successfully be grown in minimum or zero tillage systems on different soil types. Moreover, the growth of fibre flax in these systems does not compromise such essential quality parameters as a high proportion of tall plants having thin stems and minimal branching.

4.2. Introduction

Reduced tillage is a concept that has existed for many decades (Baker et al., 1996), but only more recently, and for a variety of reasons, have producers increasingly begun to adopt reduced tillage systems (Lafond et al., 1996). Reduced soil erosion and improved water infiltration are two benefits which can directly be attributed to increased crop residues on the soil surface (Lafond, 1993; Lafond et al., 1993; Opoku & Vyn, 1997). Other potential advantages of reduced tillage are fuel conservation, time flexibility at seeding time, improved soil structure and improved soil organic matter (Baker et al., 1996).

Tillage regime greatly influences seedbed quality, with conventional tillage most often resulting in a light, fluffy seedbed (Baker et al., 1996). This is in contrast to direct seeding or zero tillage, in which seedbeds tend to be harder and compacted, with substantial crop residue remaining on the surface. Minimum tillage systems tend to occupy an intermediate position with seedbeds having a lumpy to fine consistency, depending on the extent of residue management and crops employed in the rotation.

Early and uniform establishment is crucial to the success of fibre flax crops for a number of reasons. Fibre flax is often seeded to attain populations of 2000 plants m^2 (Sultana, 1983; Robert, 1995; Stephens, 1997), so even a partial delay in emergence can result in a highly non-uniform stand, as plants which emerge late are at a competitive disadvantage (Fowler, 1984). Uniformity is a desirable characteristic in fibre flax destined for linen production, as the length of fibres will influence the price a producer obtains for the crop (Ulrich & Laugier, 1995). Stand uniformity is affected by seedbed preparation as well as seed placement (Lafond et al., 1996).

Some work has been carried out examining the performance of oilseed flax in reduced tillage systems. Results indicate that establishment and seed yield in these systems can be excellent (Gubbels & Kenaschuk, 1989a; Gubbels & Kenaschuk, 1989b;

Lafond et al., 1993). Although flax is a cool season crop with moderate frost hardiness (Fouilloux, 1989), some evidence suggests deep seeding in cool, moist soils (such as those found in minimum tillage systems) can result in both delayed emergence, and lower stand density (O'Connor & Gusta, 1994). Despite these findings, little is known about how fibre flax might perform in a reduced tillage rotation.

In 1998, research was initiated at Macdonald Campus of McGill University to evaluate the performance of fibre flax (cv. Ariane) in three different tillage systems: conventional tillage (CT, minimum of two tillage operations), minimum tillage (MT, maximum of two tillage operations), and direct seeding or zero tillage (ZT, no tillage operations). This assignment of tillage terms follows one suggested by Lafond et al. (1996) which categorizes a tillage system by a discrete number of tillage operations.

4.3. Materials and methods

Research was conducted in 1998 at two sites at Macdonald Campus, McGill University, Ste. Anne-de-Bellevue, Québec, Canada (45° 25' 45" N lat., 73° 56' 00" W long.). One site was on a Bearbrook clay soil (poorly drained, Dark Grey Gleysolic, pH 6.53) (Lajoie, 1960), which was in soybean in 1997 (hereafter referred to as the soybean site) and barley in 1996. The other site was on a Chicot fine sandy loam (moderately well drained, Gray Brown Podzolic, pH 5.94) (Lajoie, 1960), which was in oats in 1997 (hereafter referred to as the oat site) and red clover in 1996 and 1995.

Land preparation procedures for these experiments were the treatments being assessed. The conventional tillage (CT) plots included fall moldboard plowing in the fall of 1997 followed by disking and cultivation in the spring of 1998. The minimum tillage (MT) plots were disked once and then a second time at an angle of 90° in the spring of

1998. The zero tillage (ZT) plots received no cultivation, and a chemical burndown was not required due to the early time of seeding and lack of emerged weeds. No fertilizer was applied at either site. The fibre flax cultivar 'Ariane' was seeded on May 1 at a rate of 125 kg ha $^{-1}$ in all plots on the same day using a Hassia DU 100 small grains drill for the CT and MT plots, and a Great Plains no till seeder for the ZT plots. Plot size was 3 m x 20 m. Row spacing for the Hassia seeder was 6.5 cm and was 25 cm for the Great Plains seeder. The experimental design was a randomized complete block with two blocks and one replicate/treatment/block.

The oat site was moderately infested with quackgrass (*Elytrigia repens* (L.) Nevski) and was sprayed with fluazifop-p-butyl (Venture®) + non-ionic surfactant (0.7 kg ai ha^{-1} + 0.5 % v/v). The test was sprayed again with bentazon (Basagran Forte®) (0.960 kg ai ha^{-1}) for annual broadleaf weed control. The soybean site was sprayed with bentazon (Basagran Forte®) (1.08 kg ha^{-1}) for control of yellow nutsedge (*Cyperus esculentus* L.). All herbicide treatments applied were applied at the recommended rates for oilseed flax according to Publication 75: Guide to Weed Control (Anon, 1997).

Climatological data (temperature, rainfall, and growing degree days) were recorded by an automatic weather station at Macdonald Campus. These data are presented in Appendix 2.1.

4.3.1. Data Collection

The data collected from all experiments aimed to assess the performance of fibre flax in reduced tillage situations compared with conventional tillage.

The number of days to emergence, flowering, and harvest were counted and considered as phenological development parameters of the plants in each treatment.

Average plant height per plot was measured three, six, and nine weeks post-emergence, as described in section 3.3.1.3 in chapter 3. Stem diameters were measured on 50 random plants per plot using a Marathon 150mm electronic digital caliper (Marathon Management Co., Richmond Hill, Ont.), and the plot means were used in the data analysis to reduce variability. Plant densities were determined in two random 50 cm x 12 cm strips. The number of plants within these strips having branches were counted, and divided by the total number of plants in the area, thus providing a branching ratio. Plant density and branching ratio data were transformed using square root + 1 to satisfy the condition of normality for the ANOVA procedure (Gomez & Gomez, 1984). Yield data were obtained from two randomly placed 50 cm x 55 cm quadrats within each plot and bulked. A 200 g sample from each plot was then dried to constant weight at 65° C in a forced air dryer.

All data collected were subjected to analysis of variance (ANOVA) using the GLM procedure in SAS (SAS Institute Inc., 1985), to identify any main effects of tillage system on the various characteristics mentioned above. Significant results ($P<0.05$) were then subjected to a Tukey's HSD means comparison procedure (Motulsky, 1995) to identify differences between treatments.

4.4. Results

The month of April in 1998 was considerably warmer and drier than usual (Appendix 2.1). The mean temperature was 2° C above normal, with only a quarter of the normal rainfall (Appendix 2.1), thus allowing seeding to take place relatively early. In fact, temperatures were above normal every month from April to September, except for July, which was 1° C below normal (Appendix 2.1). The same pattern stood for rainfall, with every month having below normal rainfall, except for June, which had 1.5 times the normal rainfall (Appendix 2.1). The number of growing degree days (base of 5° C) was correspondingly higher than the average (Appendix 2.1).

4.4.1. Oat Site

Tillage treatment had little effect on rate of germination as all plots had uniform seedling emergence by six days after seeding (Table 4.1). The number of days to flowering varied little, with the ZT plots flowering in 51 days compared with 53 and 54 days for the MT and CT plots, respectively (Table 4.1). The number of days to harvest was 85 days for all tillage treatments (Table 4.1). There were no significant ($P \geq 0.05$) differences between treatments in terms of fresh weight, plant density, or branching ratio (Tables 4.2A, B). There were significant ($P < 0.05$) differences between treatments in dry matter content (Table 4.2A). The ZT plots had the highest dry matter content (38%), compared with 34% and 33% for the CT and MT plots, respectively (Table 4.2A). Stem diameter was also found to differ significantly ($P < 0.05$) between treatments (Table 4.2A). Plants in the ZT plots had the lowest average stem diameter (1.87 mm), compared with plants in the CT plots (2.21 mm) and the MT plots (2.07 mm) (Table 4.2B). Treatments were found to have highly significant ($P < 0.01$) effects on plant height at all three sampling dates (Table 4.2C). At the first sampling date, plants in the ZT plots (11.9 cm) and MT plots (11.1 cm) were taller than plants in the CT plots (9.5 cm) (Table 4.2C). At the second sampling date, the MT plots had the tallest plants, averaging 45.3 cm (Table 4.2C). The ZT plots had the shortest plants (37.1 cm) tall, and the CT plants were of intermediate height, averaging 42.2 cm (Table 4.2C). This same pattern was also found at the final sampling date, with plants in the MT plots being tallest (84.9 cm), CT plants of intermediate height (83.4 cm), and ZT plants the shortest (79.8 cm) (Table 4.2C).

4.4.2. Soybean site

All plots showed consistent emergence by six days after seeding, regardless of tillage treatment (Table 4.1). Fibre flax plants in the ZT plots were flowering after 54 days, and the MT and CT plots after 56 days (Table 4.1). All plots were harvested 96 days after seeding (Table 4.1). There were no significant ($P \geq 0.05$) effects due to tillage treatment in plant stem diameter, branching ratio, fresh weight, plant density or dry matter content (Tables 4.2A, B). In addition, there were no significant differences ($P \geq 0.05$) between the tillage treatment in average plant height at either the first or third sampling date (Table 4.2C). Plants in the ZT plots averaged 42.1 cm in height at the second sampling date, which was significantly greater than plant heights for the CT and MT plots, which averaged 37.1 and 24.1 cm, respectively (Table 4.2C).

4.5. Discussion

Due to the unusually warm weather, seeding occurred in the third week of April. Many workers cite low soil temperature (such as those often found in ZT systems) as problematic since it can retard crop emergence time and the vigour of young seedlings (O'Connor & Gusta, 1993; Lafond et al., 1996). This was not the case at either of our sites as all the tillage treatments resulted in uniform emergence of fibre flax seedlings exactly six days after seeding. There was also little difference within sites and between sites in the number of days plants required to attain the flowering stage. Plants at the soybean site however, required an additional 11 days to attain maturity, relative to the plots in the oat site. This result may have been due to the increased nitrogen available for vegetative growth, consequently delaying maturity. Such an effect has been noted elsewhere (Couture, unpublished data).

Results between the two sites were inconsistent, with more significant results due to tillage treatment occurring at the oat site than at the soybean site. There were differences in magnitude between the sites. For example, the yield of the MT plots were similar at both sites, however the ZT and CT plots yielded nine and seven t ha $^{-1}$ more fresh biomass respectively, at the soybean site than at the oat site. In fact, overall yields at the soybean site were higher than those at the oat site (Fig. 4.1). These results appear consistent with previous findings suggesting fibre flax yields better in slightly heavier soils (Robinson & Cook, 1931; Berger, 1969; Hocking et al. 1987), and may be indicative of a potential soil type x tillage interaction. This is more likely than an effect due to the higher levels of N in the soil at the soybean site, which should not have affected the treatments differentially.

The difference in parameters measured between the two sites was also reflected in the mean plant density (Fig. 4.2), mean branching ratio (Fig. 4.3), and in mean stem diameter (Fig. 4.4). Plant density was greater across tillage treatments at the soybean site (Fig. 4.2), and mean stem diameter was correspondingly lower (Fig. 4.3). For undetermined reasons however, mean branching ratio was much higher at the soybean site (Fig. 4.4), which is inconsistent with reports of higher plant density resulting in plants with fewer branches (Hocking et al., 1987).

Comparisons of tillage systems in oilseed flax in Western Canada indicate notable growth and (grain) yield advantages for flax grown in ZT systems compared with CT systems (Gubbels & Kenaschuk, 1989a; 1989b; Lafond, 1993). Our results suggest that fibre flax grown in a ZT system would produce shorter plants having less biomass, leading to fewer and shorter fibres overall (Robinson, 1933), which is consequential for linen production but not for industrial use (Foster et al., 1997; 1998). Interestingly, plants in the ZT plots in both sites had a greater mean plant height at three weeks post-emergence at the oat site, and until six weeks post-emergence at the soybean site. This suggests that concerns of lower soil temperatures negatively affecting plant development did not materialize. Plant densities were also greater in the ZT plots despite the greater row spacing, which is consistent with the findings of Gubbels & Kenaschuk (1989a; 1989b). This greater plant density likely led to the lower average stem diameter, and lower branching ratios for plants in the ZT plots in both sites, as intra-specific plant competition for light became more intense. Easson and Long (1992) reported similar results of intra-specific plant competition in fibre flax, also observing reduced overall plant height.

Overall, there was no effect of tillage treatment on fresh weight or branching ratio at either site, suggesting that quantity and quality of fibre is likely not to be affected to a great extent by tillage practices. The results at the oat site indicate that the lower yield and mean plant height in the ZT treatment may be offset by greater plant density. Differences between treatments were even less pronounced at the soybean site, with fresh biomass yield, plant density and final plant height not being greatly affected by tillage system. However, plants within the MT treated plots yielded the greatest amount of fresh biomass, despite these plots having the lowest mean plant densities of all tillage treatments. These findings indicate that fibre flax could be produced successfully in a reduced tillage or zero tillage system, however a seeder with a narrower row spacing than 25 cm would be advantageous, and would likely result in greater population densities, and ultimately taller plants.

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Table 4.1. Phenological development of fibre flax (cv. Ariane) grown under different tillage systems in two sites.

	Soybean site			Oat site		
Treatment	Days to emergence	Days to flowering	Days to harvest	Days to emergence	Days to flowering	Days to harvest
CT	6	56	96	6	54	85
MT	6	56	96	6	53	85
ZT	6	54	96	6	51	85
Mean	6	55.3	96	6	52.7	85

CT Conventional tillage.
MT Minimum tillage.
ZT Zero tillage.

Table 4.1A. Comparison of plant density, branching ratio and stem diameter means for various tillage treatments at two sites at Macdonald Campus in 1998.

Treatment	Mean plant density (m^2)		Mean branching		Mean stem diameter (mm)	
	Site					
	Oat	Soybean	Oat	Soybean	Oat	Soybean
CT	1253	1689	0.007	0.024	2.21 a	1.94
MT	1233	1475	0.017	0.029	2.07 ab	1.86
ZT	1311	1683	0.004	0.003	1.87 b	1.93
m.s.d.	---	---	---	---	0.33	---
Significance						
Tillage	NS	NS	NS	NS	*	NS
C.V.	11.1	8.8	1.0	2.7	2.7	9.0

Significant at $P < 0.05$.
CT Conventional tillage.
MT Minimal tillage.
ZT Zero tillage.
m.s.d. Minimum significant difference.
Significant at $P < 0.05$.
NS Not significant.
C.V. Coefficient of variation.
a, b Values within a column followed by the same letter do not differ at the $P \geq 0.05$, according to Tukey's HSD test.

Table 4.1B. Comparison of mean yield for various tillage treatments at two sites at Macdonald Campus in 1998.

Treatment	Mean fresh weight t ha^{-1}		Mean dry matter content (%) [a]	
	Site			
	Oat	Soybean	Oat	Soybean
CT	19.3	26.8	34 b	37
MT	27.4	30.2	33 b	36
ZT	17.2	26.4	38 a	35
m.s.d.	---	---	---	---
Significance				
Tillage	NS	NS	*	NS
C.V.	11.3	1.5	6.3	4.8

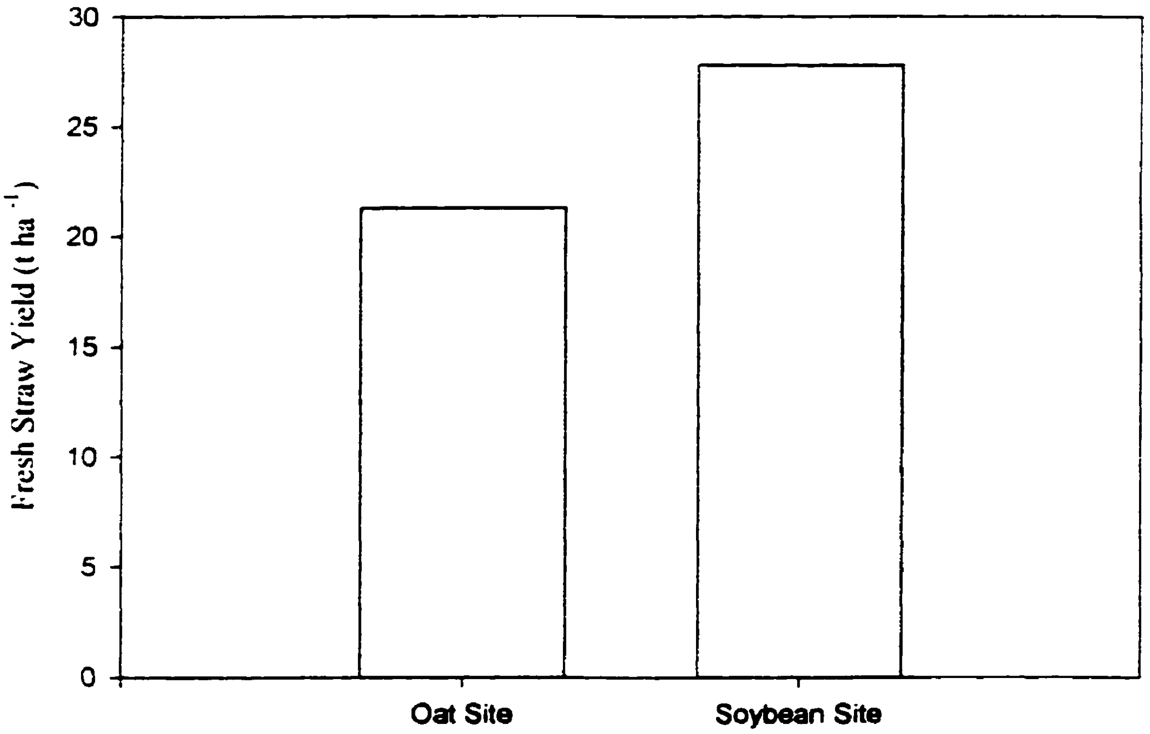
[a] Means comparison based on dry weights, not percentages.
CT Conventional tillage.
MT Minimum tillage.
ZT Zero tillage.
Significant at $P < 0.05$.
NS Not significant.
m.s.d. Minimum significant difference.
C.V. Coefficient of variation.
a, b Values within a column followed by the same letter do not differ at the $P \geq 0.05$, according to Tukey's HSD test.

Table 4.1C. Comparison of mean plant height at different sampling dates for various tillage treatments at two sites at Macdonald Campus in 1998.

Treatment	Mean plant height three weeks post-emergence (cm)		Mean plant height six weeks post-emergence (cm)		Mean plant height nine weeks post-emergence (cm)	
	Site					
	Oat	Soybean	Oat	Soybean	Oat	Soybean
CT	9.5 b	9.6	42.2 ab	37.1 b	83.4 ab	83.4
MT	11.1 a	10.0	45.3 a	34.1 b	84.9 a	83.9
ZT	11.9 a	10.5	37.1 b	42.1 a	79.8 b	81.5
m.s.d.	1.5	---	6.2	3.64	3.9	---
Significance						
Tillage	**	NS	**	***	**	NS
C.V.	16.0	15.1	17.5	11.2	5.5	5.1

CT Conventional tillage.
MT Minimum tillage.
ZT Zero tillage.
m.s.d. Minimum significant difference.
, * Significant at $P < 0.01$ and $P < 0.001$ levels of probability, respectively.
NS Not significant.
C.V. Coefficient of variation.
a, b Values within a column followed by the same letter do not differ at the $P \geq 0.05$, according to Tukey's HSD test.

Figure 4.1. Comparison of mean fibre flax fresh straw yield at two sites at Macdonald Campus in 1998, across three tillage systems.



30
25
20
15
10
5
0
Fresh Straw Yield (t ha $^{-1}$)
Oat Site
Soybean Site

Figure 4.2. Comparison of mean fibre flax plant density at two sites at Macdonald Campus in 1998, across three tillage systems.

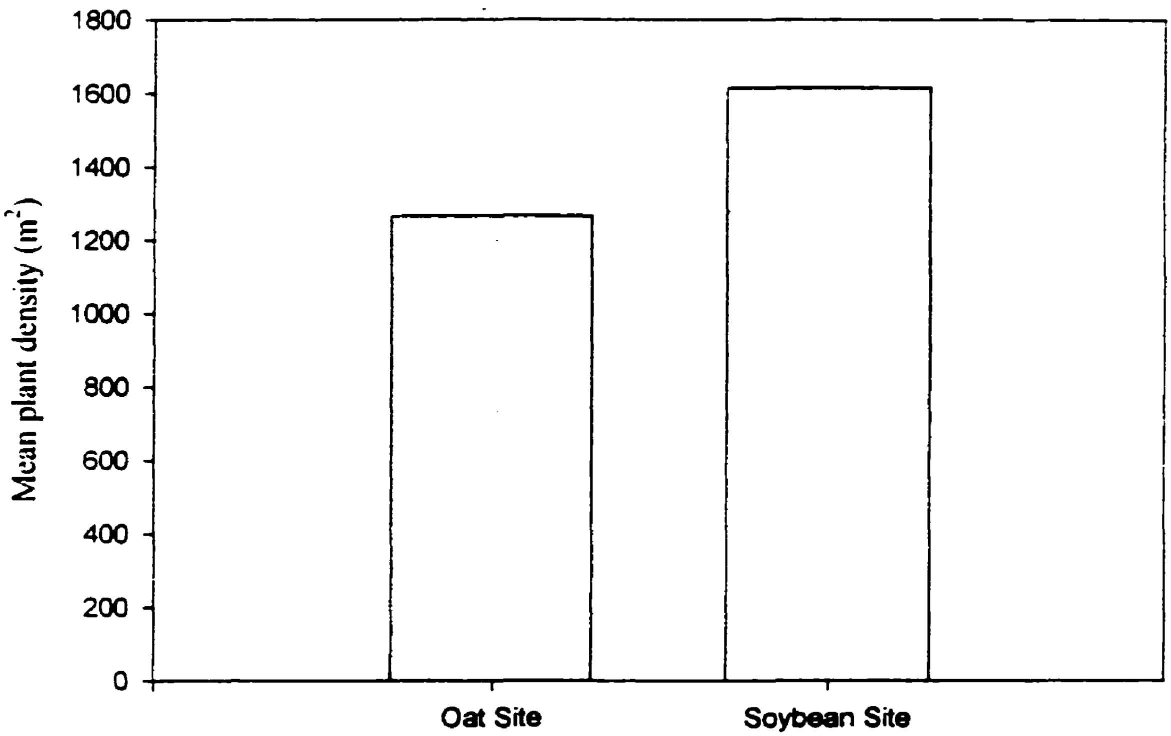
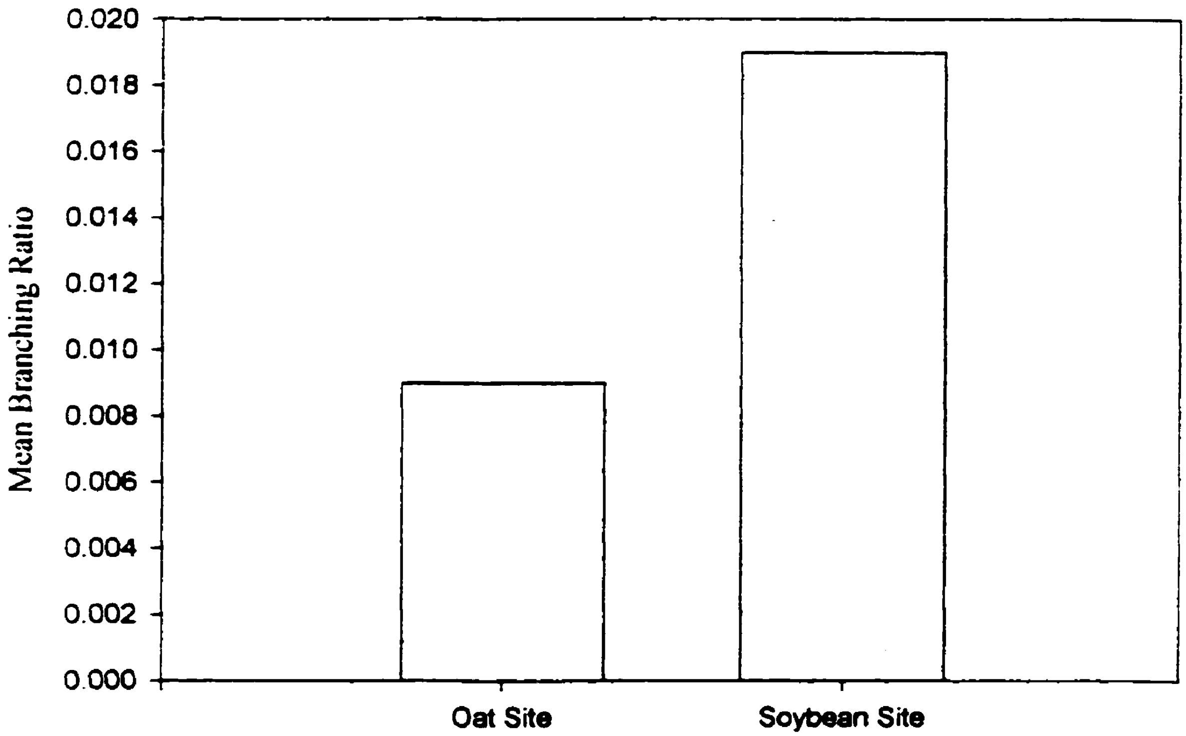
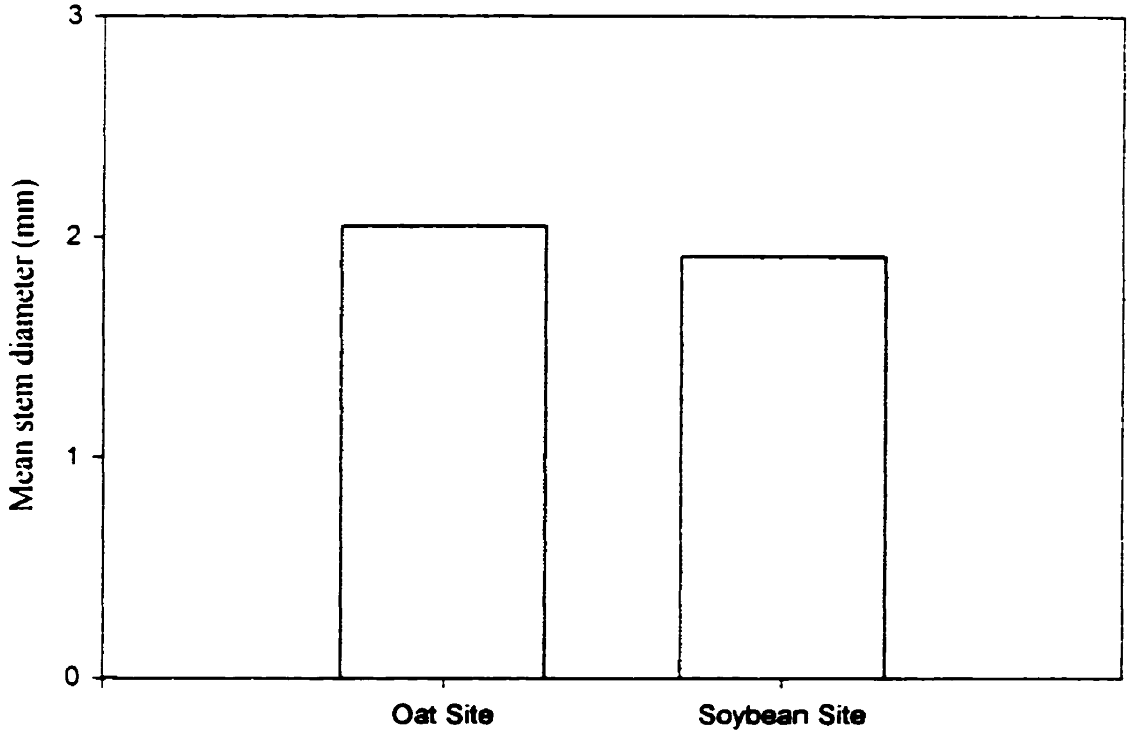

1800
1600
1400
1200
1000
800
600
400
200
0
Mean plant density (m^{2})
Oat Site
Soybean Site

Figure 4.3. Comparison of mean fibre flax branching ratio at two sites at Macdonald Campus in 1998, across three tillage systems.



0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Mean Branching Ratio
Oat Site
Soybean Site

Figure 4.4. Comparison of mean fibre flax stem diameter at two sites at Macdonald Campus in 1998, across three tillage systems.


3
2
1
0
Mean stem diameter (mm)
Oat Site
Soybean Site

Chapter 5. General Conclusions

This research investigated the potential of producing fibre flax using cultivars of European origin in Québec and Eastern Ontario, Canada. Research was also conducted to evaluate a variety of methods for the establishment of fibre flax in terms of seeding depth and soil compaction, as well as the cultivation of fibre flax under conventional, minimal, and zero tillage regimes. The impact of these factors was evaluated in relation to fibre flax growth parameters including stem diameter, branching ratio, plant density, plant height, and biomass yield. The results stemming from this research should permit a more rigorous evaluation of fibre flax cultivars, to be grown successfully under Québec and Eastern Ontario growing conditions.

The results of the cultivar trials across the two years indicated significant differences between cultivars in a number of the parameters measured. Cultivars also appeared to react differently to different soil types, although this effect was not confirmed statistically. The French cultivar 'Ariane' proved to be the most versatile in both years, yielding acceptable quantities of straw from tall plants. Differences in seed size and germinability also proved to be key factors affecting cultivar performance, with the cultivar 'Belinka' exhibiting low germination and subsequent poor yield performance at all sites in 1998.

Research conducted on the effects of seeding depth and soil packing (rolling) on fibre flax growth and subsequent performance indicated no significant effect due to rolling alone in either year of the study. Seeding depth did have variable results on fibre flax performance, with soil type and weather conditions possibly playing an interactive role. A shallow seeding depth of one to four centimeters was found to provide consistent fibre flax emergence regardless of soil type. Effects of seeding depth on yield were significant at two sites in 1997. At the Bearbrook clay site a seeding depth of two centimeters yielded the most retted straw, and at the St. Amable sandy loam site a depth of one centimeter yielded the most retted straw, followed by a depth of two centimeters. There was a significant interaction between seeding depth and rolling on retted straw yield at all sites in 1997. Our findings suggest that shallow seeding after rolling of the seedbed provides better yields in lighter soils, while shallow seeding without any rolling of the seedbed results in higher yields in heavier soils.

The results of the tillage experiments in 1998 indicated more significant results at the oat site (loam soil) than at the soybean site (clay soil), and again, there may have been a treatment by site interaction that was not confirmed statistically. Plants in the soybean site had thinner stem diameters, higher populations and higher yields overall, across the various tillage treatments. At the oat site, the minimum tillage plots produced the tallest plants at the end of the season, whereas plants grown on zero tillage plots had significantly thinner stems than plants grown in the conventional tillage plots. The minimum tillage plots had significantly lower fibre flax populations at the soybean site, and the lowest (non-significant) plant populations at the oat site. However, plants in the minimum tillage plots produced the greatest yields compared with the other tillage treatments at both sites (non-significant).

Based on the findings of this research, there appears to be no obvious agronomic or climatological reasons for fibre flax production not to resume in Eastern Canada after a long absence, especially given that markets for linen and industrial applications of flax fibres have been growing at a rapid pace over the last few years. The cultivar 'Ariane' should be considered as a standard for Eastern Canada. Fibre flax growth appears to fare well under minimum tillage conditions, thus increasing crop rotation and tillage options for Eastern Canadian producers adopting this crop. Finally, seeding depth and soil compaction have an impact on fibre flax performance, but these factors must be considered in the light of the soil type on which the fibre flax is grown. Overall, the inclusion of fibre flax production within Eastern Canadian agricultural cropping systems will likely lead to a greater diversification of production systems and additional economic returns for producers.

Chapter 6. Contributions to Knowledge.

The following are considered to be key contributions to knowledge arising from the research described in this thesis:

1. This is the first study in North America to include the European fibre flax cultivars Argos, Diane, Evelin, Hermes, Raisa, and Viola.
2. This is the first study in North America to evaluate soil packing as a component of the seeding operation in the cultivation of fibre.
3. To the candidate's best knowledge, this is the first study ever to evaluate the performance of fibre flax in minimum and zero tillage systems.

Appendix 2.1. Climatic data for the growing seasons of 1997 and 1998 at Macdonald Campus and at Kemptville.

	1997, Ste Anne-de-Bellevue, Qc.						1998, Ste. Anne-de-Bellevue, Qc.						1998, Kemptville, Ont.	
	Rainfall (mm)	Norm (mm)	Mean Temp (° C)	Norm (° C)	Growing Degree Days [y]	Norm	Rainfall (mm)	Norm (mm)	Mean Temp (° C)	Norm (° C)	Growing Degree Days [y]	Norm	Rainfall (mm)	Mean Temp (° C)
April	139.2	70.0	4.9	5.9	56.2	73.0	26.0	70.0	7.9	5.9	304.4	73.0	39.3	8.3
May	78.5	70.8	10.7	13.1	177.3	256.7	58.8	70.8	16.8	13.1	365.0	256.7	50.8	16.5
June	88.0	88.3	19.5	18.1	435.0	396.3	137.7	88.3	18.8	18.1	414.8	396.3	129.6	18.7
July	161.7	89.7	20.0	21.1	466.4	496.7	75.2	89.7	20.2	21.1	471.5	496.7	139.0	20.1
August	138.2	99.9	18.5	19.8	417.2	457.2	79.0	99.9	20.0	19.8	465.9	457.2	128.8	19.6
Sept.	96.7	97.9	14.2	14.7	275.8	291.3	46.1	97.9	15.5	14.7	313.7	291.3	97.2	15.0
Season Total	702.3	516.6	N/A	N/A	1827.9	1971.2	422.8	516.6	N/A	N/A	2335.3	1971.2	584.7	N/A

Source: Environment Canada

[y] Base of 5° C

Appendix 3.1. Analysis of variance for the seeding depth trial at the Bearbrook clay site in 1997.

	TPD	Tratio	Retted straw	Ht1
Block	***	*	***	NS
Roll	NS	NS	NS	NS
Depth	*	NS	***	NS
Block*Roll	NS	NS	*	**
Block*Depth	NS	NS	***	NS
Roll*Depth	NS	NS	***	NS
C.V.	23.0	10.1	14.0	10.6

*, **, ***, Significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$ levels of probability, respectively.
NS, Not significant.
TPD Transformed values of plant density.
Tratio Transformed values for branching ratio.
Ht1 Plant height prior to harvest.
C.V. Coefficient of variation.

Appendix 3.2. Analysis of variance for the seeding depth trial at the St. Amable sandy loam site in 1997.

	TPD	Tratio	Retted straw	Ht1
Block	NS	NS	NS	NS
Roll	NS	NS	NS	NS
Depth	*	NS	*	NS
Block*Roll	**	NS	***	NS
Block*Depth	NS	NS	NS	*
Roll*Depth	NS	*	*	NS
C.V.	25.2	11.9	18.6	6.4

*, **, ***, Significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$ levels of probability, respectively.
NS Not significant.
TPD Transformed values of plant density.
Tratio Transformed values for branching ratio.
Ht1 Plant height.
C.V. Coefficient of variation.

Appendix 3.3. Analysis of variance for the seeding depth trial at the Macdonald clay site in 1997.

	TPD	Tratio	Retted straw	Ht1
Block	*	**	NS	***
Roll	NS	NS	NS	*
Depth	NS	*	NS	NS
Block*Roll	NS	NS	NS	NS
Block*Depth	NS	NS	NS	NS
Roll*Depth	NS	**	**	**
C.V.	26.8	12.1	23.6	8.2

*, **, ***, Significant at P < 0.05, P < 0.01, and P < 0.001 levels of probability, respectively.
NS Not significant.
TPD Transformed values of plant density.
Tratio Transformed values for branching ratio.
Ht1 Plant height.
C.V. Coefficient of variation.

Appendix 3.4. Analysis of variance for the seeding depth trial at Macdonald in 1998.

	Diam	TPD	Tratio	Fresh weight	Dry weight	Ht1	Ht2	Ht3
Block	***	NS	NS	***	NS	***	***	***
Roll	NS	NS	NS	NS	NS	NS	NS	NS
Depth	*	NS	NS	NS	NS	*	NS	**
Block*Roll	*	*	NS	*	***	**	***	***
Block*Depth	NS	NS	NS	NS	NS	NS	*	NS
Roll*Depth	**	NS	NS	NS	NS	NS	NS	**
C.V.	6.34	11.5	2.1	12.6	6.04	15.2	7.3	4.2

*, **, ***, Significant at P < 0.05, P < 0.01, and P < 0.001 levels of probability, respectively.
NS Not significant.
Diam Stem diameter.
TPD Transformed values of plant density.
Ht1, Ht2, Ht3 Plant heights at three, six, and nine weeks post emergence.
C.V. Coefficient of variation.