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Conservation Practices in Western Oregon Perennial Grass Seed Systems: II. Meadowfoam Rotation Crop Management

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ABSTRACT

Rapid changes in practices used to produce perennial grass seed crops in the U.S. Pacific Northwest region and shortened lengths of time that perennial grass seed fields remain in production have increased the need for additional rotation crops that are adapted to the poorly drained soils found in western Oregon. This research was conducted at three sites to determine ways to manage meadowfoam (*Limnanthes alba* Hartw. ex Benth.) as a component in perennial grass seed rotation systems. Experiments were conducted in 1997, 1998, and 2001 to investigate combinations of spring-applied herbicide and N fertilizer and times of applications, direct-seeded and conventional tillage establishment methods, and previous crop residue management on meadowfoam seed yield, seed oil concentration, and oil yield. No spring-applied fertilizer or herbicide produced responses for all yield components as great as or greater than any other treatment combination. Direct-seeded meadowfoam yielded more oil than the conventional establishment treatment. There was no effect of residue management amounts from grass seed grown in the previous rotation sequence on meadowfoam production; however, maximal residue management, especially if used in combination with direct-seeded meadowfoam, should reduce annual soil erosion. Meadowfoam is suited to low-input production and is adapted to the use of conservation practices including direct seeding and maximal residue management in perennial grass seed systems.

There has been a rapid change in the practices used to produce perennial grass seed crops in the U.S. Pacific Northwest. Because of air quality and public safety concerns, postharvest straw burning was reduced to 10% of the historic high by 1998 in maritime western Oregon. Also, a majority of the grass seed crop now being produced is private turf-type cultivars with increased market demands for new cultivars, in contrast to earlier times when public forage cultivars dominated the market (Meyer and Funk, 1989). As a result, the length of time that seed fields remain in production has shortened to as few as 3 or 4 yr, compared with times past when stands were established for 10, 20, or more years. Because grass seed crops readily shatter when reaching maturity, added pressures have been placed on seed growers to meet genetic purity standards when changing cultivars of the same grass species (Mueller-Warrant et al., 1995; Young and Youngberg, 1996).

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Grass seed crops are adapted to the poorly drained soils found throughout the southern Willamette River basin of western Oregon. The economic value of grass seed crops combined with limited choices of alternative rotation crops that are adapted to these conditions greatly limit the rotation crop options available to growers. When rotation crops are used, the primary selections have been white clover seed (*Trifolium repens* L.) or wheat (*Triticum aestivum* L.).

Meadowfoam has emerged as an additional rotation crop option for perennial grass seed production systems. This crop is a small herbaceous winter–spring annual that grows 20 to 40+ cm tall. Native meadowfoam was originally found in vernal pools in northern California and southern Oregon pastures, with its name derived from the white blooming canopies of plants that give the image of white foam covering the ground. Flowering stems arise in late winter to early spring from a rosette. The leaves are pinnately dissected with incisely toothed, lobed, or parted stems. The fibrous root system penetrates the soil to a depth of 150 cm. Vegetative growth is terminated in late spring when temperatures rise. Meadowfoam favors low temperatures during flowering and seed formation (Pearson, 1983; McGahuey, 1986; Franz and Jolliff, 1989; Franz et al., 1992), which can be problematic for pollinator bee (*Apis mellifera* L.) activity needed to ensure pollination (Jahns and Jolliff, 1990). Meadowfoam damaged by springtime-applied herbicide is characterized by button- rather than pear-shaped buds that either do not open or have shriveled or distorted flower petals (O.G. Hoffman, personal communication, 2005). Meadowfoam produces high quality oil comprised of C_{20} and C_{22} fatty acids, with Δ^5 unsaturation (Miller et al., 1964; Higgins et al., 1971; Nikolava-Damyanova et al., 1990). These oil characteristics give this crop potential for use in the production of lubricants, cosmetics, rubber additives, and plastics (Hirsinger, 1989; Burg and Kleiman, 1991), or biodiesel.

There is limited information available describing how meadowfoam would respond in perennial grass seed production systems. Perennial grass seed crops typically require N fertilizer applications to achieve optimal economic yields, but there is a growing amount of evidence that excess residual N in the soil following seed production may have an adverse affect on meadowfoam yields (G.D. Jolliff, personal communication, 2005). Meadowfoam seed yield and seed oil

Abbreviations: H+F+, herbicide plus fertilizer applied at the normal time; H+F−, herbicide applied at the normal time but without fertilizer; H+Fd, herbicide applied at the normal time with fertilizer application delayed; H−F+, fertilizer applied at the normal time without herbicide; H−F−, no herbicide or fertilizer applied; HdF+, fertilizer applied at the normal time but the herbicide application delayed; HdF−, herbicide application delayed and no fertilizer applied.

concentration are reduced when N fertilizer is applied at 80 kg ha^{-1} or more, compared with no application of fertilizer (Jolliff et al., 1993a, 1993b). Also, meadowfoam yields can be greatly reduced by the meadowfoam fly (*Scaptomya apicalis*), whose damage is increased with increasing amounts of applied N fertilizer (Panasahatham et al., 1999).

Perennial grass seed production has been shown to benefit from the use of direct seeding and maximal residue management, compared with the standard practice of burning or removing straw by baling after seed harvest (Steiner et al., 2006). There is no information, however, reporting the effects of the practices on meadowfoam production. Therefore, the purpose for this research was to determine how to manage meadowfoam as a rotation crop component in perennial grass seed production systems using conservation practices suited to western Oregon.

MATERIALS AND METHODS

Experiment Locations

A series of meadowfoam experiments were conducted in 1996–1997 (1997), 1997–1998 (1998), and 2000–2001 (2001) at three locations in the Willamette Valley, Oregon, as a part of a 10-yr experiment investigating the effects of conservation practices on perennial grass seed production (Steiner et al., 2006). The general treatment arrangements at each of the three long-term experiment locations were four main plots, each approximately 18 m wide by 30 m long and all arranged in a randomized complete block design. This plot configuration accommodated a total of six or seven treatments per location. All main plots throughout the duration of the 10-yr experiment were managed with two 15-m-long subplots to accommodate residue amounts when grass seed was grown.

The primary research site used in 1997, 1998, and 2001 was on a commercial farm in Linn County (44°28′56″ N, 123°11′01″ W; 76-m elevation). The soil was a poorly drained Amity silt loam (fine-silty, mixed, superactive, mesic Argiaquic Xeric Argialboll) marginally suitable for perennial grass seed production. Additional plots used in 1998 were on a moderately drained Woodburn silt loam (fine-silty, mixed, superactive, mesic Aquultic Argixeroll) site in Benton County at the Hyslop Research Farm (44°38′01″ N, 123°12′01″ W; 70-m elevation), and on a commercial farm with a Nekia silty clay loam on 2 to 12% slopes (fine, mixed, active, mesic Xeric Haplohumult) in Marion County (44°56′24″ N, 123°45′19″ W; 236-m elevation). The 1997 experiment conducted at Linn County was considered a preliminary experiment. Experiments conducted in 1998 and 2001 were the primary contributors of results in this study.

Meadowfoam Management

Plot preparation for planting by conventional tillage was done using a tractor-powered rototiller (3 m wide) mounted on a three-point hitch to simulate the multiple tillage operations used by farmers. Following tillage, the plots were rolled twice to firm the seeding bed for planting. Direct-seeded establishment plots had no tillage applied before planting.

In 1997 and 1998, 4.7 L ha^{-1} of glyphosate [*N*-(phosphonomethyl)glycine] was applied before planting to both the conventional tillage and direct-seeded plots. In 2001, glyphosate plus 2.3 L ha^{-1} of clopyralid (3,6-dichloro-2-pyridinecarboxylic acid) was applied before planting. In 1998 and 2001, 4.9 kg ha^{-1} of metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide] was applied preemergence to all plots in autumn after planting. A tractor-mounted spray-boom applicator was used to treat the entire plot area.

Both direct-seeded and conventional disturbance plots were planted with commercial double-disk openers (John Deere, Moline, IL) attached to a Hege 80 plot-style planter frame (Hege Seedmech, Colwich, KS) (Steiner et al., 2006). In all experiments, meadowfoam 'Flora' (Jolliff, 1994) was planted at 28 kg ha^{-1} in rows 0.15 m apart and 25 mm deep. Planting dates for all experiments are given in Table 1.

Honey bees at 5 hives ha^{-1} were placed each year next to each experimental site for pollination at the beginning of flowering time, and removed when flowering had ceased. Meadowfoam seeds were harvested using a Carter flail plot-scale forage harvester (Carter Manufacturing, Brookston, IN). The material was collected in burlap bags and immediately dried in a walk-in, gas-heated drier for 24 h at 30°C, and then weighed. Seed yield was determined after the seeds were separated from plant material using a Saugluftstufensichter Type 2 round-screen seed thresher fitted with a 4-mm-square screen (Kurt Pelz Saatmeister, Badgodesberg, Germany). Seed oil concentration was determined by infrared spectrophotometry by the method reported in Jolliff et al. (1993b) using a Minispec PC 120 (Bruker Spectrospin Canada Ltd., Milton, ON). Oil yield was determined as the product of seed yield and seed oil concentration. Total plant phytomass was determined by subtracting the weight of the seeds from the initial harvested plot dry mass.

Experiment Descriptions

Experiment 1: Spring-Applied Herbicide and Fertilizer Timing

The experiment was conducted at Linn County in 1988 and 2001 with meadowfoam establishment by direct-seeded planting. Seven combinations of spring-applied herbicide (H) and fertilizer treatments (F) were applied. The mixture of herbicides (spring herbicide regime) was comprised of: 0.58 L ha^{-1} of clethodim (2-[(1*E*)-1-[[[(2*E*)-3-chloro-2-propenyl]oxy]imino]propyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one); 3.2 L ha^{-1} of sethoxydim (2-[1-(ethoxyimino)-butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one); and 0.37 L ha^{-1} of clopyralid (3,6-dichloro-2-pyridinecarboxylic acid). These are the only spring-applied herbicides registered for meadowfoam production in Oregon. A mixture of herbicides are used to control a range of grassy and broadleaf weeds that otherwise would be problematic in perennial grass seed crops. The fertilizer amount applied was 45 kg ha^{-1} of N in the form of N-2-benzothiazolyl-N′-methylurea.

The herbicide and fertilizer treatments were either made at times when producers would normally make applications to their fields (19 and 16 March in 1998 and 2001, respectively), delayed after the normal time (14 and 24 April in 1998 and 2001, respectively), or not applied. Periods of precipitation during late-winter rainfall may affect when farmers can apply herbicides, so this perspective was used to choose the timing of applications. Also, reductions in production costs, such as not using herbicides, would increase the net return from a meadowfoam crop grown in rotation with more profitable grass seed crops.

The herbicides and fertilizer combinations (chemical treatments) used in this experiment were: (i) herbicide plus fertilizer applied at the normal time (H+F+); (ii) herbicide applied at the normal time, but without fertilizer (H+F−); (iii) herbicide applied at the normal time, with fertilizer application

Table 1. Locations, years, establishment methods, and previous crops in the rotation used to determine the effects of production practices on meadowfoam grown in western Oregon in 1998 and 2001 within a 10-yr experiment that began in 1992 and ended in 2001.

Experiment†	Location	Year	Establishment method‡	Prior crop§	Planting date
			Exp. 1: Fertilizer–herbicide treatment combinations		
Preliminary	Linn County	1997	B	WC	23 Oct. 1996
1-1	Linn County	1998	DS	WC	23 Oct. 1997
1-2	Linn County	2001	DS	WC	11 Nov. 2000
			Exp. 2: Direct seeding and conventional tillage establishment		
2-1	Linn County	1998	B	WC	23 Oct. 1997
2-2	Linn County	1998	DS	WHT	23 Oct. 1997
2-3¶	Benton County	1998	B	RC	16 Oct. 1997
2-4	Benton County	1998	CT	TF	16 Oct. 1997
2-5	Marion County	1998	DS	WHT	25 Oct. 1997
2-6	Linn County	2001	DS	WC	11 Nov. 2000
			Exp. 3: Grass straw management amount		
3-1#	Linn County	1998	DS	WHT	23 Oct. 1997
3-2	Benton County	1998	CT	WHT	16 Oct. 1997
3-3	Linn County	2001	DS	WC	11 Nov. 2000
			Exp. 4: Relay-planted tall fescue		
Relay					
4-1	Benton County	1998	DS	RC	16 Oct. 1997
Tall fescue	Benton County	1999	DS	MF	9 Mar. 1998
Conventional					
4-2	Benton County	1998	DS	TF	16 Oct. 1997
Tall fescue	Benton County	1999	CT	MF	19 Oct. 1998

† Experiments are comprised of the combined results from the subsets of studies listed below. Listed under each of the four experiments are the descriptions of the trials. Exp. 1: results were based on data from a preliminary experiment and two repeated experiments (1-1 and 1-2). Exp. 2: results were based on data from six experiments. Exp. 3: results were based on data from three experiments. Exp. 4: results were based on direct-seeded and conventional tillage established meadowfoam (4-1 and 4-2, respectively), with tall fescue relay seeded by direct seeding in spring and conventional tillage established in autumn.
‡ DS, direct seeded; CT, conventional tillage establishment; B, both establishment methods compared.
§ MF, meadowfoam; RC, red clover seed; TF, tall fescue seed; WC, white clover seed; WHT, spring wheat.
¶ This experiment was also used to determine the effects of relay seeding tall fescue into autumn direct-seeded meadowfoam.
# Data used for the paired comparisons of residue management amounts in Exp. 3-1, 3-2, and 3-3 correspond to the treatments in Exp. 2-2, 2-4, and 2-6, respectively.

delayed (H+Fd); (iv) fertilizer applied at the normal time, but without herbicide (H−F+); (v) no herbicide or fertilizer applied (H−F−); (vi) fertilizer applied at the normal time, but the herbicide application delayed (HdF+); and (vii) herbicide application delayed, and no fertilizer applied (HdF−).

The seven herbicide–fertilizer treatment combinations were assigned at random within each of the two 15-m-long split plots within each main plot area. Each chemical treatment plot was approximately 2 m wide and 15 m long. The experiment was repeated in 2 yr. The herbicide treatments were applied each year with a backpack type sprayer using a wand-type boom fitted with nozzles. The fertilizer was applied with a tractor-mounted granular fertilizer applicator (Gandy Co., Owatonna, MN) that straddled each plot.

An ANOVA was done as a split-plot randomized complete block design with the hierarchy: years (Y) > blocks (B) > split plots (S) > herbicide–fertilizer treatment combinations (T). The model for this design was

$$y_{ijkl} = \mu + Y_i + B_j + YB_{ij} + \delta_{(ij)} + T_k + YT_{ik} + YBT_{ijk} + YBTS_{ijkl} + \varepsilon_{(ijkl)}$$

The restrictions on randomization were represented in the model by $\delta_{(ij)}$, the restriction error. The YBTS interaction mean square was used to test the T main effect and YT interaction. Duncan's new multiple range test was used to determine mean differences among the herbicide–treatment combinations (Damon and Harvey, 1987, p. 165). Orthogonal mean comparisons (Sokal and Rohlf, 1981, p. 233) within the seven herbicide–fertilizer treatment combinations were made to test for differences among herbicide treatment levels, fertilizer treatment levels, and specific combination contrasts. Fisher's protected least significant difference test (Snedecor and Cochran, 1980, p. 234) was used to show differences among herbicide–fertilizer treatment combination means within production years.

Experiment 2: Direct-Seeded Meadowfoam

Results from six experiments (Trials 2–1 through 2–6, Table 1) conducted at the three sites were pooled to compare direct seeding with conventional tillage treatments (T). The experiment was analyzed as an unbalanced randomized block design with the model

$$y_{ijkl} = \mu + B_i + \delta_{(i)} + T_j + BT_{ij} + \varepsilon_{(ij)}$$

with the restrictions on randomization represented in the model by $\delta_{(i)}$, and the treatment effect (T) tested by the BT interaction. Fisher's protected least significant difference test was used to show differences among establishment methods. The pooled data approach followed the method described in Steiner et al. (2006).

In addition, soil compaction measurements were taken on 17 Mar. 1997 using a DICKEY-john Soil Compaction Tester (DICKEY-john Corp., Auburn, IL) in the preliminary experiment at the Linn County site for each of the four block replications of the direct-seeded and conventional tillage establishment plots. Compaction measurements were taken at five randomly selected locations within each plot at eight soil depth intervals: 0 to 7.6, 7.6 to 15.3, 15.3 to 22.9, 22.9 to 30.5, 30.5 to 38.1, 38.1 to 45.7, 45.7 to 53.3, and 61 cm. These data were analyzed as a randomized complete block design. Only the results from the first four depths are reported. Seedling emergence counts were also made for six 1-m lengths of planted row in each plot. The effects of establishment methods on soil compaction and seedling emergence were assumed to be applicable to the results that would have been obtained under the 1998 and 2001 conditions.

Experiment 3: Grass Seed Crop Residue Amount

Grass seed preceded meadowfoam in three experiments as either the immediate crop prior or two crops prior in the rotation sequence in Trials 2–2, 2–4, and 2–5. High and low grass seed straw residue amount treatments from the three experiments were compared. These data were analyzed as a split-plot randomized complete block design with the analysis hierarchy: experiment (E) > blocks (B) > residue amount treatment (R). The model for this design was

$$y_{ijkl} = \mu + E_i + B_j + EB_{ij} + \delta_{(ij)} + R_k + ER_{ik} + BE_{jk} + EBR_{ijk} + \varepsilon_{(ijk)}$$

The restriction on randomization was represented by $\delta_{(i)}$, the first restriction error. The mean square for EBR was used to test residue treatment and the EB interaction.

Experiment 4: Spring Relay-Planted Tall Fescue into Meadowfoam

Comparisons were made of the effects of tall fescue establishment systems after meadowfoam using either direct relay seeding of tall fescue into meadowfoam in spring or conventional tillage to establish tall fescue seeded in autumn. A randomized complete block design was used for the analysis. Subsequent tall fescue seed yields were determined in 1999, 2000, and 2001 harvest years. The analysis was done using a split-plot randomized complete block design with the analysis hierarchy: seed harvest year (S) > blocks (B) > establishment system (E). The model for this design was

$$y_{ijkl} = \mu + S_i + B_j + SB_{ij} + \delta_{(ij)} + E_k + SE_{ik} + BE_{jk} + SBE_{ijk} + \varepsilon_{(ijk)}$$

The restriction on randomization was represented by $\delta_{(i)}$. The mean square for SBE was used to test the treatment main effects and the SE interaction. The effect of the establishment systems on 3-yr total tall fescue seed yield was also tested using a randomized complete block design. Differences among establishment system means within years were determined using Fisher's protected least significant difference test.

The relationship between meadowfoam seed yields and seed oil contents was plotted for all treatment combinations from each of the individual experiments (Exp. 1 and 2) conducted in 1998 and 2001 (Table 1). The data were fitted with a nonlinear function using TableCurve 2D software (Systat Software, 2006).

The Revised Universal Soil Loss Equation (RUSLE) using RUSLE 1.06c software was used to estimate the annual amount of soil erosion (RUSLE *A*) for the meadowfoam crop component. The production calendar for RUSLE was based on a 15 August start date. Greater details about the RUSLE *A* estimates are given in Steiner et al. (2006). The specific RUSLE parameters used are available on request.

A partial budget approach (Carkner, 2005) was used to compare cost differences to prepare fields for planting by conventional tillage and direct seeding following nonselective herbicide applications. Because a rototiller was used to simulate tillage in our plots, a telephone census of six farmers was conducted to determine the typical kinds and number of tillage operations needed to prepare fields using conventional tillage. The costs of the nonselective herbicide used in field preparation before seeding meadowfoam was based on farmer cost in the region (US\$10.46 L^{-1}), and associated amounts of nonselective herbicide required to kill the preceding crops (Steiner et al., 2006).

RESULTS AND DISCUSSION

Experiment 1: Spring-Applied Fertilizer and Herbicide Timing

There was a range of responses by meadowfoam seed yield, seed oil content, and oil yield (all yield components) to the seven fertilizer–herbicide treatment combinations (Table 2). In all cases, the F−H− treatments produced responses for all yield components that equaled or exceeded any other treatment combination (Fig. 1).

Experiment Context

The combinations of fertilizer and herbicide treatments were chosen after a preliminary experiment was conducted in 1997 that attempted to determine the effects of establishment method and N fertilizer application amounts on meadowfoam production. Annual bluegrass (*Poa annua* L.), an emerging weed problem in grass seed fields that were not burned after harvest (Mueller-Warrant and Rosato, 2002a, 2002b), was abundant in the 1997 experiment and not adequately controlled without autumn-applied metolachlor, especially in the fertilized plots. As a result, meadowfoam seed yields were highly variable and there were no differences due to the N fertilizer rates or establishment method (data not shown). It was observed, however, that annual bluegrass growth was greatly reduced by spring herbicide applications in the plots that received no N fertilizer compared with plots that received N fertilizer. Annual bluegrass plants in the no-N plots also became infested by powdery mildew (*Erysiphe graminis*) (M. Azevedo, personal communication, 1997).

We hypothesized that annual bluegrass would be more susceptible to the spring-applied herbicides if the N fertilizer application was delayed until powdery mildew infestations were present. Delaying the N fertilizer application would also allow greater meadowfoam competition with the annual bluegrass before the herbicide was applied. Annual bluegrass was observed to grow more aggressively after spring fertilizer N application

Table 2. Probability values from the analysis of variance results of eight treatment combinations with orthogonal contrasts for fertilizer and herbicide applications used on meadowfoam grown at Linn County in western Oregon in 1998 and 2001.

		Significance		
Sources of variation	df	Seed yield	Oil conc.	Oil yield
Years (Y)	1	ns†	*	ns
Treatments (T)	6	***	***	***
Orthogonal treatment contrasts				
Among fertilizer (F) treatments within herbicide (H+) treatments	2	*	ns	*
Among H treatments within F+ and F− treatments	2	***	***	***
F × H: among H and F (+ and −)	1	ns	ns	ns
Y × T	6	***	***	***

* Significant at $P \leq 0.05$.
*** Significant at $P \leq 0.001$.
† ns, not significant at $P \leq 0.05$.

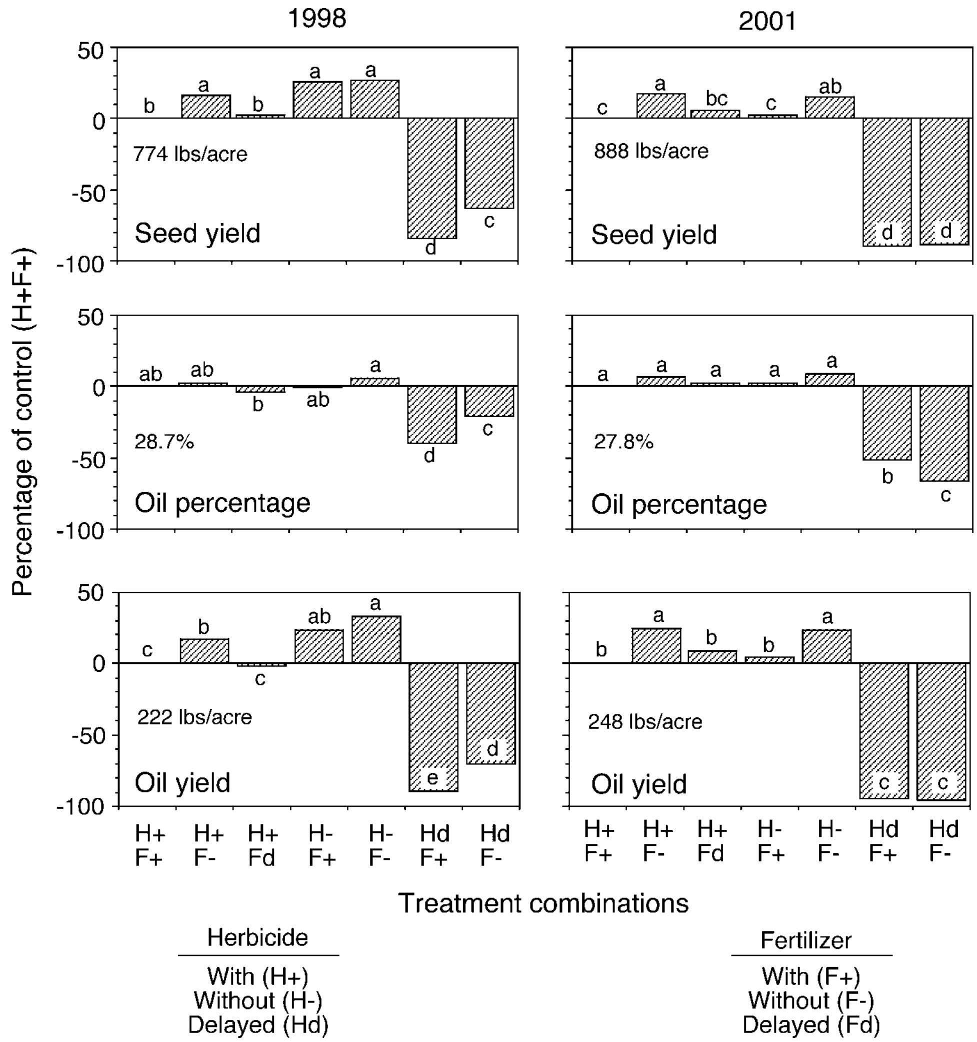

Fig. 1. Effects of seven spring-applied fertilizer and herbicide treatments on seed yield, oil concentration, and oil yield of meadowfoam grown as a rotation crop for perennial ryegrass seed on a poorly drained soil in western Oregon in 1998 and 2001. The H+F+ control treatment is the combined application of herbicide and fertilizer at typical spring timing after weed seedlings have begun to emerge. The mean seed yield, seed oil content, and oil yield for each control in both years is shown in each graph. Bars within each graph shown with the same letter are not different at $P \leq 0.05$ according to Duncan's new multiple range test.

than the meadowfoam (Steiner, unpublished data, 1997). These observations were used to design the fertilizer–herbicide treatment combinations used in 1998 and 2001 at Linn County (Table 1).

Fertilizer Treatment Effects

The no-N treatment plots produced greater seed and oil yields than the mid-March-applied or delayed treatments (Table 3). Seed oil concentration was not affected by the fertilizer treatments. In the only other reports of N applications on meadowfoam production, seed yield and seed oil concentration were reduced when fertilizer was applied at 80 kg ha^{-1} or more in late February compared with no fertilizer applied (Jolliff et al., 1993a, 1993b). Nitrogen application amounts >80 kg ha^{-1} may cause excessive vegetative growth that adversely affects the yield components (Jolliff et al., 1993b). Our 45 kg ha^{-1} application amount was about half the amount used by the other researchers, and further substantiates

Table 3. Treatment contrast results for the effects of N fertilizer and herbicide timing on seed yield, seed oil content, and oil yield of meadowfoam grown in Linn County in 1998 and 2001.

	Fertilizer			Herbicides		
Parameter	**Yes**	**No**	**Delayed**	**Yes**	**No**	**Delayed**
Seed yield, kg ha^{-1}	**933.9b†**	**1087.2a**	**969.4b**	**1010.5b**	**1085.6a**	**168.8c**
Oil concentration, g kg^{-1}	**282.6**	**292.6**	**280.1**	**287.6a**	**292.6a**	**151.4c**
Oil yield, kg ha^{-1}	**264.0b**	**318.4a**	**272.1b**	**291.2b**	**317.5a**	**30.1c**

† Means within rows that are followed by a different letter are not significant at $P \leq 0.05$ according to Fisher's protected least significant difference test.

that meadowfoam grown in this region does not need N fertilization. Seed growers have also reported no yield differences when comparing commercial fields either receiving or not receiving N fertilizer applications (G. Pugh, personal communication, 1988).

Herbicide Treatment Effects

The intent of the spring herbicide application was to control, without open-field burning, annual bluegrass and other grassy weed infestations that initially increased in grass seed fields with the introduction of mechanical residue management methods (Mueller-Warrant and Rosato, 2002a, 2002b). The herbicide regimes used for broadleaf rotation crops are also desired to reduce seed production of grassy weeds that are difficult to control in perennial grass seed crops.

Regardless of the timing of the spring herbicide regime, however, meadowfoam seed and oil yields were adversely affected by these herbicides compared with the no-herbicide treatment (Table 3). Seed and oil yields were more adversely affected by the delayed mid-April application time than the earlier application in mid-March (Table 4). Seed oil concentration was only decreased with the delayed herbicide application. Progressively more flowering buds are damaged with increasing delay of herbicide applications after early March (Hoffman, personal communication, 2005).

In this experiment, inclusion of the autumn-applied metolachlor regime resolved any annual bluegrass problem that may have occurred, as was observed in the 1997 preliminary experiment. Any weeds that are not controlled by the preplant and pre-emergence herbicides can be controlled by a spring-applied herbicide regime; however, we observed few weeds remaining in the plots in the spring following the autumn-applied herbicide applications. So if the spring-applied herbicide regime is used, then it appears that the earlier it is applied to emerged annual bluegrass seedlings, the better.

Table 4. Effects of seed production year and herbicide–fertilizer treatment combinations on meadowfoam seed oil concentration in western Oregon in 1998 and 2001.

Treatment†		Oil conc.			
Herbicide	Fertilizer	1998	2001	Difference‡	Avg. oil conc.
		g kg^{-1}			g kg^{-1}
Yes	yes	287.0	278.3	ns§	282.6a¶
Yes	yes	291.4	293.8	ns	292.6a
Yes	delayed	276.5	283.6	ns	280.1a
No	yes	284.3	284.5	ns	284.4a
No	no	301.8	299.8	ns	300.8a
Delayed	yes	154.4	133.3	**	143.8b
Delayed	no	226.5	91.4	***	158.9b

** Significant at $P \leq 0.01$.
*** Significant at $P \leq 0.001$.
† Yes, applied at a time commonly used by producers; no, not applied; delayed, application delayed later than the usual time.
‡ Difference is for the comparison of oil concentrations in 1998 and 2001.
§ ns, not significant at $P \leq 0.05$.
¶ Means for averages of oil concentrations in 1998 and 2001 followed a different letter are significant at $P \leq 0.05$ according to Duncan's new multiple range test.

The spring herbicide regime is effective only with emerged weeds, however, so there is reason to delay the application time to get the greatest control efficacy. Under these growing conditions, annual bluegrass has peak emergence periods in late November and early April (Steiner, unpublished data, 1999), so the mid-March application time could miss some weed seedlings with delayed emergence. The tradeoff with delayed herbicide application is the adverse effects it has on oil yield (Fig. 1). The lowest seed yielding treatment combinations also had the lowest seed oil contents (Fig. 2), indicating that not only are the number of florets produced reduced, but also the capacity of seeds to produce oil. There were no interactions between the H−F− treatment and mid-March fertilizer and herbicide combination treatments (H+F−, H−F+, and H+F+; Table 2). Practically, given the negative impacts of spring-applied herbicides on seed oil content, farmers should pay particular attention to spring herbicide use based on need and anticipated efficacy for needed weed control.

Conservation Practices

Experiment 2: Direct Seeding Establishment

Meadowfoam average seed and oil yields were greater when using direct seeding than conventional tillage establishment (Table 5). Seed oil concentration was unaffected by the establishment method.

Preliminary research conducted in 1997 showed that the tilled soil layer of poorly drained Amity silt loam soils at Linn County became saturated with water when winter precipitation began. As a result, the soil was less resistant to a penetrometer probe to the depth of the tillage layer than the untilled soil (Table 5). The soil became more resistant at the depth below the tillage layer, and then was similar to that of the untilled soil.

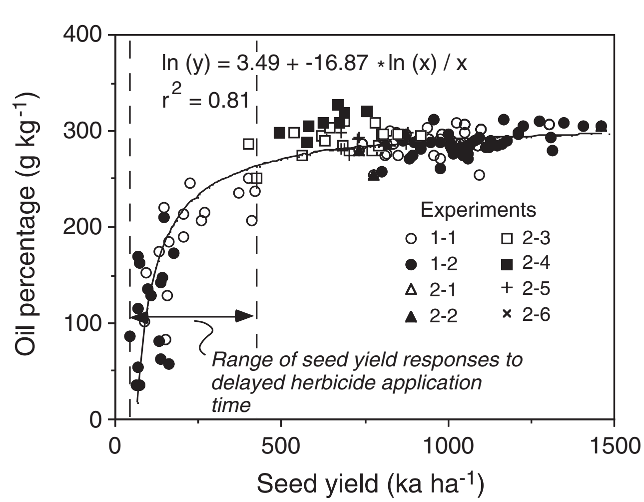

Fig. 2. The effect of the resulting seed yields on oil concentration in 1998 and 2001 from all fertilizer and herbicide treatment (Exp. 1), and direct seeding and conventional tillage establishment treatments (Exp. 2). Vertical broken lines show the range of seed yields resulting from delayed herbicide application treatments used in Exp. 1.

Table 5. Comparison of the effects of direct seeding and conventional tillage establishment on meadowfoam grown in western Oregon.

						Penetrometer depth, cm‡			
Establishment method	Seed yield†	Oil conc.	Oil yield	Total phytomass	Emergence	0–76	76–152	152–228	228–304
	kg ha^{-1}	g kg^{-1}	kg ha^{-1}		plants m^{-2}	kPa			
Direct seeding	827.1	287.4	237.5	3037.9	415.3	779.7	759.0	855.6	952.2
Tillage	643.2	288.9	189.3	2011.8	230.7	448.5	586.5	1035.0	903.9
Difference	***	ns§	***	*	***	**	*	*	ns

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.
*** Significant at $P \leq 0.001$.
† These data were obtained from three sites in 1997, 1998, and 2001.
‡ These data were obtained from the Linn County site in 1997.
§ ns, not significant at $P \leq 0.05$.

The unstable soil in the conventional tillage plots also resulted in fewer emerged seedlings and less total plant phytomass than the direct-seeded establishment treatment. Also, soil that was tilled for autumn planting cannot be driven on by farm equipment without substantial tire traffic marks until the soil drains in the spring.

Another benefit from using direct seeding compared with conventional tillage was the reduced cost of establishment. The cost savings for meadowfoam after tall fescue, red clover, wheat, and white clover are US$102.50, $114.70, $127.00, and $78.10 ha^{-1}, respectively. It is estimated that >60% of the commercial meadowfoam acreage is now planted by direct seeding (Jolliff, 2004).

Experiment 3: Residue Management Amount

There were limited experimental combinations to compare the effects of preceding maximal and minimal grass seed crop residue amounts on meadowfoam production. For the three experimental combinations with grass straw residue amount comparisons, the amount of residue left on the plots had no effect on the meadowfoam yield components (average meadowfoam seed yields for maximal and minimal residue management amounts were 777 and 740 kg ha^{-1}, respectively). These results are similar to those reported from farmer field trials (Jolliff, 2004). Three species of grass seed crops also were unaffected when comparing minimal and maximal straw amounts (Steiner et al., 2006).

An advantage for using maximal residue management when producing meadowfoam is the estimated reduction in soil erosion, compared with growing meadowfoam following a crop managed with minimal residue amounts (Fig. 3). Maximal residue management used in combination with direct seeding has only 2.8% of the annual erosion that occurs in conventional tillage grass seed systems with minimal residue management. Meadowfoam seeded in late November and December does not provide great amounts of ground cover during the winter months until the canopy begins to expand in spring. The typical remaining residue amounts for minimal and maximal chopped straw for the three grass seed crop systems used are between 1800 and 12 000 kg ha^{-1} after seed harvest (Steiner et al., 2006). Therefore, when meadowfoam is grown in rotation following perennial grass seed crops using direct seeding and maximal residue amount conservation practices, the resulting impact from meadowfoam with relatively poor soil cover on soil erosion by precipitation should be greatly mitigated. This is especially evident comparing the 83% reduction in soil erosion using direct-seeded meadowfoam following creeping red fescue managed with maximal residue management when grown on steep slopes with erodable soil (Fig. 3). These findings follow general observations from field-scale, on-farm trials (O.G. Hoffman and G.D. Jolliff, personal communication, 2005).

Experiment 4: Tall Fescue Seed Relay Establishment

The stability of the soil in direct-seeded meadowfoam provides additional crop management options for perennial grass seed production. Tall fescue can be direct seeded in the spring as a relay crop into already established autumn-planted meadowfoam. This can be done while the meadowfoam plants are in the small rosette development stage without an adverse effect on seed yield (Table 6). This allows a unit of land to produce income each year without the loss of revenue that otherwise occurs during the establishment year of a conventional spring-established tall fescue seed crop (Steiner et al., 2006). Autumn-planted tall fescue produced a reduced seed crop the following summer (Table 6), so only a portion of the income lost during the establishment year would be gained, compared with the typical winter-fallow system with spring planting that yields a full

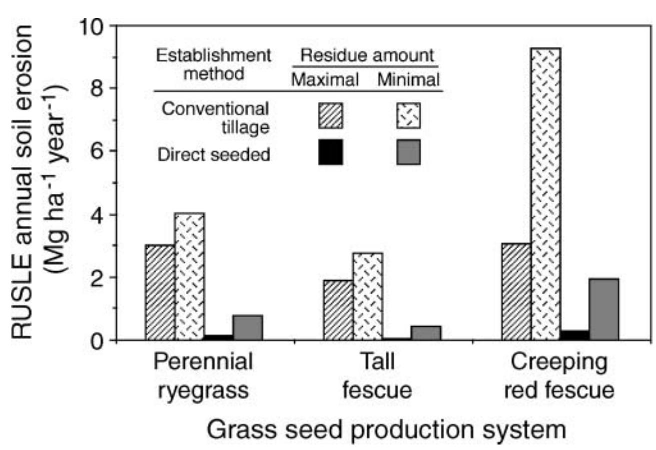

Fig. 3. Estimated annual soil erosion amount from autumn-planted meadowfoam as affected by conventional tillage and direct-seeding establishment methods and maximal and minimal amounts of postharvest straw returned to fields following perennial grass production. The annual amount of soil erosion was estimated by the Revised Universal Soil Loss Equation (RUSLE).

Table 6. Comparison of meadowfoam and tall fescue seed yields at the Benton County site from autumn established meadowfoam with tall fescue relay-planted by direct seeding in spring compared to tall fescue planted by conventional tillage in spring after winter fallow. Tall fescue seed yields were determined for three crop years during the period from 1999 to 2001.

Crop rotation component	Establishment system: Relay-planted direct seeding	Conventional tillage	Establishment system difference
	kg ha^{-1}		
Meadowfoam	653.9	710.1	ns†
Tall fescue seed year			
First	873.2	135.4	**
Second	1619.7	1594.6	ns
Third	1768.1	1521.9	**
Total tall fescue	4261.0	3251.8	**

** Significant at $P \leq 0.01$.
† ns, not significant at $P \leq 0.05$.

crop but requires 1 yr to establish without income. When using autumn tillage to prepare fields for planting, a perennial grass seed crop cannot be established by relay or conventional establishment methods the next spring until soil conditions become stable after the soil drains.

CONCLUSIONS

This research determined the suitability of meadowfoam as a rotation crop in temperate perennial grass seed production systems in western Oregon in the maritime Pacific Northwest ecoregion. Meadowfoam is suited to low-input production and is adapted to conservation practices including direct seeding and maximal residue management. Therefore, meadowfoam can be included as a rotation crop in perennial grass seed production systems that do not require tillage for establishment or removal of straw by baling or burning. Meadowfoam did not require a supplemental application of N fertilizer to achieve maximum yield, and in fact had reduced yields with the application of N. The suite of spring-applied herbicides used to control any grassy or broadleaf weeds decreased seed yield, especially if application time was delayed. Use of spring-applied herbicides decreased both the seed yields and seed oil content. The lower cost of establishment using direct seeding also provides an additional benefit compared with conventional tillage establishment. Concurrent with lower establishment costs, the use of direct seeding and maximal residue management should also reduce soil erosion when this crop with poor canopy cover is inserted into a perennial grass seed production rotation.

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