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Balancing Forage Production, Seed Yield, and Pest Management in the Perennial Sunflower *Silphium integrifolium* (Asteraceae)

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Abstract: The perennial sunflower *Silphium integrifolium* Michx. (Asteraceae), also known as silflower, is a prospective dual-purpose forage plus grain crop. Pre-flowering biomass harvest for animal feed and the subsequent delay in plant growth and anthesis has the potential to benefit seed yield and/or offset yield loss from native pests, such as the native North American *Eucosma giganteana* (Lepidoptera: Tortricidae). The aim of this study was to develop a cropping technology for silflower to (A) balance forage and grain production and (B) minimize seed loss. Silflower produced high-quality forage, but biomass harvest in early spring reduced same-season seed production by 45%. Despite significantly delaying flowering, forage harvest alone did not effectively reduce *Eucosma* colonization, although treating plants with the insecticide permethrin did reduce colonization. Our results do not support the proposal that *S. integrifolium* could be profitably harvested for both high quality forage and as an oilseed grain within the same season. Nevertheless, our findings suggest the possibility of developing a strategy of alternating between forage or seed production, depending on their differential economic values. The choice between harvesting biomass vs. seed could be made much later in the season for this perennial crop than the choice of planting an annual forage vs. annual grain crop.

Keywords: *Silphium integrifolium*; dual-purpose crop; forage; silage; *Eucosma giganteana*; permethrin

1. Introduction

Domestication, as defined by Stetter et al. [1], is the process of adaptation to agro-ecological environments and human preferences by anthropogenic selection. According to this definition the domestication process is a continuum, beginning with the cultivation of wild plants and progressing to the development of staple food crops. The domestication of wild plants involves a dramatic change of habitat and plant form. Through conscious or unconscious human mediated selection, rare versions of genes that make plants easier to grow and harvest, higher yielding, more palatable and nutritious—either pre-existing in the wild population or arising as new mutations—become more common in the populations under selection, generation after generation, until no wild-type variation for the most important traits remains and all plants in the domesticated population share these traits [2].

A major determinant of the success of domesticates was the utility a plant offered to early societies. Annual plants have been very successful as domesticates, because the shortened generation time speeds up response to selection [1]. In the last 50 years, agricultural productivity has increased by

more than three times thanks to the introduction of new technologies, improved high-yield crop varieties and high-input production [3]. Unfortunately, this form of production is widely associated with environmental degradation and ecosystem disservices including soil erosion, nutrient runoff or leaching, pest spread and resistance (pathogens, weed and insects), a loss of biodiversity and organic matter depletion due to soil disturbance prior to sowing and the application of fertilizers and pesticides to support production [4,5].

Adebiyi et al. [6] suggest that radical transformative technologies are needed to avoid the tradeoffs between grain production and sustainability. The cultivation of perennial grains is part of these radical transformations. However, over more than 10,000 years of plant domestication, not one perennial species was domesticated for grain production [7]. While it is widely accepted that a shift from annual to perennial cereal varieties could significantly reduce the environmental footprint of agriculture whilst meeting the demands for yield [8–10], it has proved challenging to obtain perennial grains that are simultaneously agronomically productive, environmentally sustainable, and economically viable. One approach to increase the feasibility of perennial grains is to focus on multifunctionality and different benefits that perennial grain crops might provide beyond grain production, including forage production, and regulatory ecosystem services such as protection of soil resources, regeneration of soil health, conservation of biodiversity, and improvement of agroecosystem resilience [11]. This approach is based, as much as possible, on the use of natural resources (produced on the farm or obtained from other farmers) and ecological principles [12].

Several species of *Silphium* L., perennial relatives of the annual crop sunflower (*Helianthus annuus* L., Asteraceae), are being domesticated as oilseed crops (*S. integrifolium* [10]), biogas substrates (*S. perfoliatum*; [13,14]) or fodder [15,16], but none have been assessed as a dual-purpose crop. This term refers to the use of a crop as forage for livestock, before or after grain production. These crop–livestock systems can promote farm diversification, provide flexibility in enterprise mix, and reduce risks for farmers [17]. Several annual crops, such as winter canola, triticale, maize, hemp, barley, oat and pearl millet are used as dual crops in Australia, central USA, Argentina and Europe [12,18–21]. Kansas, where annual sunflowers and *Silphium* species are native, ranks within the top five US states for sorghum silage production, sorghum grain production, cattle and calf production, and sunflower seed production [22]. This region is well-suited to grow, and could greatly benefit from, a dual-purpose crop derived from a *Silphium* species.

Ideally, harvest management of dual-purpose crops should seek to simultaneously optimize biomass and seed production. Harvest frequency, harvest timing, and plant growth are potential factors to manage in order to optimize fodder or seed yield [22]. However, practices that are optimal for one type of yield may compromise the other. For example, biomass harvest during early vegetative stages might affect crop phenology such that grain yield is reduced, as has been shown in triticale [23]. The timing of harvest and the extent of biomass removal can determine the moment of anthesis, which can compromise grain production.

These factors are also important in the context of pests, and in forage systems harvesting can even be employed as a pest management strategy to reduce the dependence of agricultural systems on pesticides and promote natural regulation of crop pests. Alfalfa cuttings and biomass removal can be timed to manage the alfalfa weevil, alfalfa blotch leafminer, beet armyworm, western yellow-striped armyworm, pea aphid, and potato leafhopper [24]. In perennial forage–grain crops, harvesting could also serve as a tactic to delay flowering to avoid peak abundance of pests. The annual oilseeds' analog to this is the delayed planting of sunflower to produce late-flowering fields [25] that are less likely to be colonized by flower-feeding pests [26]. Thus, the reduced yield loss to pests and the reduced need for insecticide applications in these later-flowering fields may offset the reduced yield of a later-flowering variety, resulting in a net economic benefit.

Silphium integrifolium, or silflower, is a prospective dual-purpose crop, for which biomass harvest and the subsequent delay in plant growth and anthesis may actually benefit seed yield or offset yield loss. Throughout its native range in the Great Plains, Midwest and Mid-South regions of North

America, silflower provides food and shelter to a variety of insects, attracting beneficial insects as well as herbivores [27]. Some of these insects affect seed yield and have become economic pests, such as the giant eucosma moth, *Eucosma giganteana* Riley (Lepidoptera: Tortricidae). Female *E. giganteana* oviposit on the flower heads of *Silphium* genus plants. Their caterpillars feed inside the flower heads during the summer, causing significant damage to the apical meristematic tissues, and then feed on the root crown during the fall [14]. *Eucosma giganteana* has been found in *Silphium perfoliatum* in South Dakota and Wisconsin [28] and in *Silphium integrifolium* in Kansas, where it can infest as many as 95% of heads by late July [29]. In *S. integrifolium* grown for oil, *Eucosma* attack would likely mean a decrease in revenue of 12–34% [27].

Given the extent of potential economic loss by stem and flower pests, we are interested in breeding for pest tolerance in silflower as one strategy to minimize the dependence on synthetic pesticides. However, as part of a sustainable integrated pest management strategy, we will need to combine selective breeding with biological and cultural practices to maintain pest populations below levels that cause unacceptable losses to seed yield. The ecological regulation of crop pest populations can be carried out by manipulating the resources used by pests in their habitats [29]. In the case of silflower, trimming plants for biomass harvest delays flowering, which may reduce the synchrony between flowering of the plant and the peak oviposition time of *E. giganteana*.

We designed two experiments as technology-generation trials to provide farmer communities with an alternative in order to move from regular insecticide and pesticides to adopting locally eco-friendly practices for the management of *Silphium integrifolium*. Different varieties of silflower are in the early stages of domestication in several locations of the US and in Patagonia Argentina. We chose two locations (Kansas, US and Patagonia, Argentina) with large differences in soil, climate and resource availability because our null hypothesis is that both populations, despite genotypical and environmental differences, will respond similarly to management.

Our objectives were to determine (i) the effect of biomass harvest on plant phenology, forage yield and grain production (dual crop); (ii) the impact of harvest intensity (from 0 to 90% aerial biomass) on plant architecture and total yield (forage + seed); (iii) the effect of phenological stage and plant architecture on *Eucosma giganteana* moth; and (iv) the effect of a broad-spectrum insecticide application (permethrin) on *Eucosma giganteana* infestations. We applied four treatments of biomass removal, differing in intensity, to provoke changes in plant phenology and architecture. As a result, we generated three phenological stages (vegetative; pre-flowering; and anthesis) at the time of year in which moths were ready to infest plants. We analyzed the collective effects of phenological delays on insect damage, forage yield, seed yield and yield components.

2. Materials and Methods

2.1. Experimental Locations

Kansas, USA: Research plots were located at The Land Institute near Salina, KS (38°46'14" N; 97°35'30" W). Soil types on the research farm include Hord silt loam (fine-silty, mixed, super active, mesic cumulic haplustolls) and Cozad silt loam (coarse-silty, mixed, super active, mesic typic Haplustolls). The location is 370 m above sea level on the western fringe of the tallgrass prairie region. Mean annual precipitation in the area is 737 mm, with approximately one-tenth of that precipitation in the form of snow. Rainfall is concentrated in spring and fall, and extended droughts are common in summer. The mean daily high temperature in July is 34 °C, the mean nightly low in January is −7 °C, and rapid, wide swings in temperature are common in all seasons. The daylength during the experiment was 11.5 h when new leaves typically emerge from the soil (mid-March) and 13 h at harvest (early September), a season of approximately 170 days, although foliage senescence does not occur until plants experience hard frosts (typically November–December). Predominant crops in the region are hard winter wheat (*Triticum aestivum* L.), grain sorghum (*Sorghum bicolor* (L.) Moench), maize (*Zea mays* L.), and soybean (*Glycine max* (L.) Merr.).

Patagonia, Argentina: Research plots were located at the Chubut River Valley (43°18′20″ S; 65°19′15″ W) near Trelew, Chubut. Soil types of the farm include clay loam to clayish soils (self-mulching, inverting soils, rich in montmorillonite clay, typic Vertisols). These alluvial soils are slightly alkaline (pH 7.1), rich in organic matter (3.5%; 0–10 cm), with 0.286% of total N, and without salinity problems (0.53 mmhos/cm). The location is 10 m above sea level on the ecotone Monte-Patagonia [30]. Mean annual precipitation in the area is 179 mm, evenly distributed throughout the year. The mean daily high temperature in January is 28.5 °C and the mean nightly low in July is 0 °C. The daylength during the experiment was 12 h in September and 10 h 50 min at harvest time. Predominant crops in the region are horticultural crops and perennial pastures such as alfalfa (*Medicago sativa* L.), tall fescue (*Festuca arundinacea* Schreb), rye grass (*Lolium multiflorum* Lam.), and tall wheatgrass (*Thinopyrum ponticum* (Podp.) Barkworth & D. R. Dewey)

2.2. Plant Description and Experimental Design

Silphium integrifolium seeds germinate in the spring, after which the plant grows very slowly and forms a rosette during the first year [16]. During late summer, vegetative buds are formed for the coming growing period [15,31], out of which the stalks form in the second year. The number of stalks per plant (10–25 stalks) increases with age [14]. There are multiple flower heads per stalk.

Our field experiments were performed in the two locations described above during their respective summer seasons: September 2017–April 2018 in Patagonia, and April–August 2018 in Kansas. Since the growth cycle in Patagonia is longer than in Kansas, we used the phenological stage of plants as criteria to determine the timing of treatments. Details of the genetic pedigree of plants used in Kansas and Argentina can be found in Vilela et al. [29]. Briefly, these agronomic experiments were performed in both locations using abandoned breeding nurseries designed to study differences between breeding lines and segregation within these lines. Thus, the individual plants were genetically non-uniform and blocks here were designed and randomized to include multiple lineages in each treatment. Overall, the breeding lineages at each location are quite similar, although not identical. They came from a breeding population under recurrent selection for an increased number of (female, seed fertile) ray florets per head (disk florets are male) and for general vigor and plant health. The founding members of this population came largely from central Kansas and represent the subspecies *Silphium integrifolium* var. *laeve*, which is differentiated from the subspecies that dominates to the south and east (var. *integrifolium*), by smooth, waxy stalks and larger seeds and heads. Wild accessions from Kansas and Nebraska are relatively genetically uniform and distinct compared with all accessions sampled and characterized by RNA resequencing in a recent study (Raduski et al, unpublished data). Groups of 24 plants of similar size and developmental stage were identified in different parts of each field (blocks) and randomly assigned to treatments within each block. In both experiments, plants were arranged 1 m apart between and within a row. Blocks were located at least 3 m from the borders of the field.

Both forage evaluation experiments had a block design with one factor (aboveground biomass removal, henceforth “trimming”), and four treatments randomly applied to two-year-old plants of each block (four plants per treatment per block; 6 blocks or replicates; 96 plants total). Measurements from each plant in each treatment/block were averaged to obtain a single data point. Each block had 16 plants and no irrigation or fertilizers were applied. Weeds were controlled manually.

Experiment 1 (Patagonia Argentina): Four trimming treatments were applied to bolted plants, 60 cm tall, in the phenological stage of pre-flowering (15 November 2017):

- Control: untrimmed.
- Mid-cut: stems trimmed above the first visible node, about 5 cm above ground level.
- Low-cut: stems trimmed at ground level.
- Low-cut_{twice}: trimmed at ground level on 15 November 2017 for the first time and on 9 February 2018 for the second time.

Experiment 2 (Kansas, USA): The same treatments were applied in Kansas on 17 May 2018. The second harvest of the low-cut_{twice} treatment was applied on 29 June 2018.

2.3. Forage and Seed Yield Determination

Biomass yield: As individual plants were trimmed by hand on the dates and heights described above; we collected the trimmed portions and obtained fresh weights at the lab. For each harvest event, 10 individual plants from each plot were oven dried at 60 °C for dry matter determination.

Forage quality: Silflower was manually harvested in both locations and directly chopped to 2–3 cm using a crop chopper. Dry matter content was determined. Forage samples were grounded through a 1 mm screen using a Thomas-Wiley model 4 mill (Thomas Scientific, Swedesboro, NJ, USA) and stored in sealed plastic sample bags.

Silage: In Kansas plants were harvested and chopped using an RCI Engineering 36A Research Plot Forest Harvester. The biomass was then bagged in approximately 15 kg samples and stored for 4 months until analysis. In Patagonia, plants were harvested and chopped with a stationary chopper to 2 cm particles. One bulk sample of ca 50 kg was bagged and stored for 4 months until analysis.

Forage samples of both locations and silage from Kansas were analyzed by Dairyland Laboratories, Inc (Arcadia, WI 54612). Dry matter (DM) was determined by oven-drying in a forced air oven at less than 60 °C until the sample contained less than 6% moisture. This was followed by NFTA (National Forage Testing Association) method 2.1.4—Dry Matter by Oven Drying—for 3 hours at 105 °C. Crude protein (CP) determination followed method 988.05 [32]. Concentrations of amylase-treated neutral detergent fiber (NDF) followed AOAC Official Method 2002.04 2005 (the modification includes the use of Sea Sand as a filter aid and Whatman GF/C filter paper for residue collection). Acid detergent fiber (ADF) was determined according to AOAC Official Method 973.18 [32]; the modification includes the use of Sea Sand as a filter aid as needed. Total digestible nutrients (TDN), net energy for growth (NE_G), and net energy for maintenance (NE_M) of experimental diets were calculated via summative equations [33]. Relative feed value (RFV) was calculated by reference to a standard digestible DM intake that was adopted to standardize a full-bloom legume forage containing 53% NDF and 41% ADF for an RFV of 100 [34]. Neutral detergent insoluble crude protein (ND-ICP) was determined by collecting the residue from the NDF method by use of Whatman 541 (nitrogen-free) paper or Whatman GF/C filter paper before analysis for nitrogen by the Crude protein method.

Silage in Argentina was analyzed by the Instituto Nacional de Tecnología Agropecuaria (Ruta 226 Km 73,5 Zipcode7620, Balcarce Buenos Aires, Argentina). Since this lab offers the analysis of only a fraction of the traits obtainable from Dairyland Lab, those data are provided in-text only. As a general reference for quality, our results were compared to the nutritional values of sorghum–sudangrass silage published in 2001 [33].

Seed yield: Seed yield potential was calculated as the number of capitula per plant multiplied by the number of mature seeds per head and by the individual seed mass (yield components). Ten capitula per plant were harvested prior to shattering and used to estimate the average number of seeds per capitulum. We allowed the capitula to air dry in the lab and then hand-threshed them and weighed 50 seeds to estimate the average seed mass. We used this adapted version of yield potential, originally defined as a maximum yield realized under non-stressful conditions [35,36], as a proxy of the reproductive allocation of the plant because (a) we did not completely control insect herbivory and (b) the evaluation of shattering resistance was not the aim of this study.

Plant phenology and architecture: After the application of treatments, individual plant phenology was observed weekly (23 July, 1, 15 and 29 August). We defined the phenological stages of *Silphium integrifolium* as follows:

Stage 1: Vegetative rosette.

Stage 2: Bolting (stems growing in height from the rosette, without visible reproductive structures).

Stage 3: Pre-flowering (visible buds, without visible ray florets).

Stage 4: Anthesis (first capitulum with ray florets fully enlarged).

Stage 5: Full bloom (multiple capitula in anthesis).

Stage 6: Capitula mostly green with loss or withering of corollas and visible seeds.

Stage 7: Mature capitula with brown seeds.

On the same dates on which phenology was recorded, the number of stalks, branches and their diameters were measured.

Pest management experiment: Insect damage to capitula and the effect of trimming treatments on the intensity of damage were evaluated only in Kansas since Patagonia has no known silflower pests. To evaluate effects of both trimming and insecticidal applications on *E. giganteana* colonization, we crossed all trimming treatments with the presence or absence of application of permethrin (3-phenoxybenzyl (1RS)-cis, trans-3-(2,2-dichlorovinyl) -2,2-dimethylcyclopropanecarboxylate, trade names include Ambush, Pounce, Nix). Permethrin is a synthetic pyrethroid compound, similar to that produced by pyrethrum flowers (*Chrysanthemum cinerariifolium* and *C. coccineum*). It is a broad-spectrum insecticide that causes neurotoxicity in multiple insect species, and has been used to manage lepidopterous pests in annual sunflowers [37,38], but it can also kill beneficial insects such as bees [39,40] and natural enemies [41].

Four stalks were randomly selected in each plant (4 plants per treatment per block/6 blocks). Two stalks were treated with 0.4% permethrin made by diluting concentrated permethrin (Permethrin 10 Livestock & Premise Spray, 36.8% permethrin Gordon's, Shawnee Kansas) with water and adding a drop of mild detergent. The remaining two stalks were untreated controls (no permethrin). The insecticide was applied weekly, at three sequential times, starting on 23 July 2018. Capitula were individually sprayed until wet with the insecticide, at a very close range.

Eucosma giganteana presence was determined by the presence of a hole boring into the flower bud (underneath or on top), and/or presence of black or grayish frass.

For each stalk, the number of flower buds infested with *E. giganteana* was recorded four times between pre-anthesis and maturity (23 July, 1 August, 15 August, and 29 August).

2.4. Statistics

We performed a two-way ANOVA to compare the treatment effect on biomass production, seed yield and yield components (capitula per plant, seeds per capitulum, seed weight) in two locations. Since the interaction between treatment and location ($T \times L$; fixed effects) was not significant for any trait, we were able to pool treatments together to compare locations, and to pool locations together to compare treatments. The effect of treatments on plant architecture (number and diameter of stalks) was evaluated only for Kansas using a one-way ANOVA. Assumptions of ANOVA were tested using a Shapiro–Wilk test for normality and Levene's test for homogeneity of variance. When these assumptions were violated, data were transformed with a logarithm (i.e., the number of capitula per plant in Patagonia).

The response of *E. giganteana* infestation to trimming and insecticide application was evaluated using a repeated measures analysis of variance of damaged capitula per plant. Total variation was decomposed into (i) between-subject variation due to insecticide effect (permethrin vs. no permethrin; fixed effect), (ii) between-subject variation due to trimming treatment effect, (iii) time effects (pre-anthesis to maturity; random effect), (iv) time and insecticide effect (v) time and trimming effect, (vi) triple interaction, and (vii) residual error variation. Since we found a significant time \times insecticide interaction ($F = 10.908$, $p < 0.001$) we analyzed the effect of time on fumigated and non-fumigated plants separately. Fisher's multiple comparisons test was used for post-hoc comparisons between permethrin vs. no permethrin. As the proportion of capitula damaged by *Eucosma* did not meet the sphericity assumption, we used a multivariate approach, an alternative that is free from this requirement [42].

3. Results

3.1. Evaluation of Silflower as a Dual-Purpose Crop

3.1.1. Biomass Production and Forage Quality

Forage yields were approximately 0.5 kg of dry biomass per plant in Patagonia, equivalent to 5 Mg DW for a density of 10,000 plants per hectare (Table 1). Plants were smaller in Kansas, yielding around 0.2 kg per plant (2 tons DW per hectare). The productivity difference is due to (a) the high incidence of several pathogens and insect pests in Kansas and no detected herbivory or disease in Patagonia, and (b) the presumed ability of silphium to access the water table in Patagonia but not Kansas, resulting in a much greater water limitation in Kansas despite the higher average rainfall. However, the relationship between the incidence of pests and pathogens and the height of the water table and plant productivity is difficult to measure and was not attempted in this case. In both locations, forage yields were reduced by 70% for the second harvest (low-cut_{twice}; data not shown). Since silflower plants are genetically heterogeneous in both locations, these locations were chosen for convenience, not to represent target production environments, and as our primary objective is to generate technology, we did not attempt to compare yields or nutrient composition between experimental sites. We checked for interactions to ensure that the response to treatments was similar in both locations, regardless of plant pedigrees and environmental differences. For forage yield, the interaction was non-significant ($F = 1.92$).

Table 1. Forage production and seed yield components of *Silphium integrifolium* plants growing in Patagonia (grey rows) and Kansas (white rows).

	Control	Mid-Cut	Low-Cut	Low-Cut _{twice}	F
Biomass Yield (kg dw plant ⁻¹)	—	0.57 ± 0.06	0.51 ± 0.03	0.51 ± 0.04	0.29 ^{NS}
	—	0.17 ± 0.02 a	0.18 ± 0.02 a	0.17 ± 0.02 a	0.32 ^{NS}
Heads Per Plant	114.28 ± 9.15 a	17.85 ± 6.14 b	13.04 ± 4.57 b	0 c	45.75 ^{***}
	316.64 ± 19.08 a	207.45 ± 20.01 b	174.65 ± 21.71 b	0 c	13.92 ^{***}
Seeds Per Head	30.77 ± 2.28	26.00 ± 2.28	21.61 ± 2.94	—	2.51 ^{NS}
	48.23 ± 2.92	46.24 ± 2.35	46.63 ± 2.23	—	0.17 ^{NS}
Seed Weight (100 seeds; g)	2.01 ± 0.16	2.14 ± 0.16	2.40 ± 0.21	—	1.14 ^{NS}
	1.86 ± 0.09	2.07 ± 0.11	2.18 ± 0.11	—	2.73 ^{NS}
Potential Seed Yield (g plant ⁻¹)	76.30 ± 4.32 a	12.42 ± 5.26 b	9.18 ± 4.82 b	—	62.77 ^{***}
	279.36 ± 24.74 a	188.98 ± 24.17 b	198.44 ± 31.60 b	—	4.11 [*]

Plants were subjected to four treatments of aboveground biomass removal: control (no trimming), mid-cut (aerial biomass trimmed above the first stalk node), low-cut (all aerial biomass trimmed once), low-cut_{twice} (all aerial biomass trimmed twice). Different letters indicate significant differences between treatments ($p < 0.05$). Comparison of means was assessed by Fisher's LSD test. F values compare treatments within a location. ^{NS}: non-significant; ^{*}: $p < 0.05$; ^{***}: $p < 0.001$.

Silflower forage and silage nutrient composition are shown in Table 2. The meaning of specific nutritional traits and a comparison with alfalfa (*Medicago sativa*) hay in full bloom, one of the most popular and highest quality fodder species both in Kansas and in Patagonia farming systems, are provided in the text. Silage nutritional traits are compared, also in the text, to sorghum silage values.

The crude protein content represents the total nitrogen (N) in the diet, which includes not only true protein but also non-protein nitrogen. Silflower hay is high in protein compared to alfalfa (21–28 vs. 14–18%). ADF refers to cellulose and lignin and it represents the least digestible fiber portion of forage. Silflower values indicate higher digestibility and thus, energy intake than alfalfa (15–19 vs. 25–40%). Neutral detergent fiber (aNDF) refers to cellulose, hemicellulose and lignin. Since silflower's aNDF content is lower than that of alfalfa (18–27 vs. 35–50%), we predict a higher feed intake. ND-ICP is an estimate of the portion of the rumen undegradable protein that is potentially available to the animal. Silflower ND-ICP is comparable to that of alfalfa (1–4 vs. 2–3%). Non-fibrous carbohydrates (NFC) represent all forms of digestible carbohydrates, indicating that silflower is a higher source of energy sources for the animal than alfalfa (41–45 vs. 22%). RFV is a forage quality term that is used to rank

feeds, especially forages, according to their overall nutritive value. The RFV of silflower forage is between 2.5- and fourfold that of full-bloom alfalfa hay (100).

Table 2. Forage and silage quality and digestibility of aboveground *Silphium integrifolium* biomass harvested during pre-flowering in Kansas and Patagonia.

	Forage		Silage
	Kansas	Patagonia	Kansas
Crude Protein, %DM	21.08 ± 2.7	27.7 ± 0.71	9.63 ± 0.63
ADF, %DM	18.97 ± 1.6	14.6 ± 0.79	42.28 ± 1.37
aNDF, %DM	27.03 ± 2.87	17.9 ± 0.71	54.53 ± 1.69
ND-ICP, %DM	1.44 ± 0.16	4.4 ± 0.12	1.44 ± 0.09
NFC, %DM	41.34 ± 3.09	45.4 ± 0.65	23.58 ± 1.15
RFV	257.98 ± 31.56	406 ± 20.5	95.69 ± 4.79
TDN-1x, %DM	74.13 ± 1.27	77.5 ± 0.62	55.93 ± 1.07
Nel-3x, Mcal/cwt	77.17 ± 1.41	81.0 ± 0.68	56.94 ± 4.79
Neg, Mcal/cwt	41.80 ± 1.99	49.6 ± 0.71	25.23 ± 0.95
Nem, Mcal/cwt	68.72 ± 2.23	77.5 ± 0.82	50.52 ± 1.03

Nutritional quality is not statistically compared between locations because the pedigree of plants is different and our objective is to provide basic information about this new crop. Mean and standard error of the mean, for $n = 4$. Each sample was a bulk of 5 individual plants. Analyses were done at DAIRYLAND LABORATORIES, INC. Arcadia, WI 54612, following standard procedures. ADF = Acid Detergent Fiber; aNDF = Neutral Detergent Fiber; ND-ICP = Neutral Detergent Insoluble Crude Protein; NFC = non-fibrous carbohydrates; RFV = Relative Feed Value; TDN = Total Digestible Nutrients Nel: net energy for lactation; Neg = net energy for growth; Nem = net energy for maintenance.

The ensilage of the cut biomass in Kansas (Table 2) resulted in a high-quality silage, comparable to that of sorghum, with higher crude protein content (9.6 vs. 6.6%), similar digestibility (ADF 41–42%), and higher predicted intake because of a lower content of cellulose, hemicellulose and lignin (aNDF 54 vs. 63%). The crude protein of silage in Argentina was similar to that of Kansas (8.9 vs. 9.6%) but NDF was lower (41 vs. 54.5%). The digestibility on a dry weight basis of this silage was similar to that of sorghum (68 vs. 64%). Data on the silage properties of biomass harvested in Argentina were mentioned here and are not included in Table 2 since the data reported is less complete (see Materials and Methods).

3.1.2. Yield Components and Seed-Yield

Potential seed yield and yield components were affected by treatments similarly in both locations (Table 1; non-significant interaction TxL). Control plants produced more seeds than the rest of the treatments. Higher yields were mainly achieved through a higher number of capitula per plant, since the number of seeds per capitulum and the individual seed weight were similar in both locations (Table 1). The lower potential yield and, specifically, the smaller number of heads per plant found in low-cut and mid-cut plants indicates that biomass harvest reduces the length of the flowering period and therefore the production of mature seeds.

Seed yield was much lower in Patagonia than Kansas. There are many potential reasons for this yield response, from differences in the genetic background of the lines used in each site, to environmental differences, which preclude the comparison of the results from both sites. Still, among these differences, we hypothesize that the ability of *Silphium* to access groundwater in Patagonia could be the cause of the different allocation pattern with a greater stalk height, branching and number of stalks. An extended vegetative phase and self-shading, due to a longer growing season in Argentina, would likely reduce seed production. The high level of plasticity depending upon resource availability suggests that ongoing domestication efforts for oilseed production should focus on breeding for a more determinate growth form with reduced stalk height and tendency to produce vegetative branches on the main stalk.

3.1.3. Harvest Effects on Phenology, Plant Architecture and Insect Damage

We evaluated the effect of biomass removal (time and intensity) on plant phenology and architecture and the impact of these changes on insect damage only in Kansas, since Patagonia is an area free of *Silphium* spp. insect pests and alterations of phenology were only relevant for seed yield.

Plant Phenology

Harvesting aboveground biomass during pre-flowering, when plants were around 60 cm in height, provoked a delay in the production of flower buds. As a result, during the regrowth period (from the end of July to mid-August in Kansas), control plants were one phenological stage ahead of late low-cut and mid-cut plants. At the end of August, all treatments were at the same phenological stage (capitula maturation; Figure 1). Plants that were harvested two times (low-cut_{twice}) did not recover. They only produced a few leaves after the second cut and never flowered (not included in Figure 1).

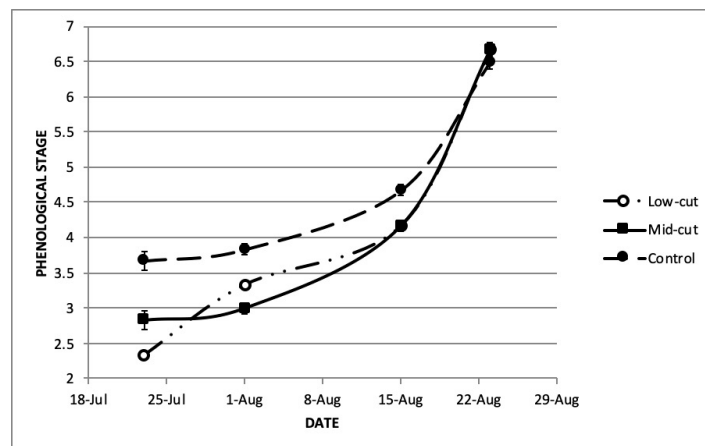


Figure 1. Phenological stages of *Silphium integrifolium* plants subjected to three treatments of aboveground biomass removal between 23 July and 29 August in Kansas. Plants subjected to low-cut_{twice} did not recover and were not included in the graph. Phenological stages: 2—bolting; 3—pre-flowering; 4—anthesis; 5—full-bloom; 6—green capitula and 7—mature capitula. Error bars denote standard errors.

Plant Architecture

Plants selected for this experiment did not differ in the number of stalks (11.67 ± 0.71 ; $F = 0.8$; $p = 0.56$) or stalk diameter prior to application of treatments (12.31 ± 1.13 ; $F = 0.93$; $p = 0.42$). When harvested, regrowth occurred from axillary leaf buds and never from buds located in the crown. As a consequence, plants produced only new branches, not new stalks. Control, and mid-cut plants retained different proportions of their stalks, with their original diameter. Low-cut plants, on the contrary, were reduced by three times the diameter of their aboveground biomass, since branches, 4.09 ± 0.27 mm in diameter, replaced harvested stalks of 12.54 ± 1.81 mm in diameter.

Response to Insecticide Application

The repeated measures analysis indicated that the proportion of capitula damaged by *Eucosma* increased over time ($F = 28.72$, $p < 0.001$) with no significant difference between all trimming treatments ($F = 0.486$, $p = 0.62$). Trimming treatments responded similarly to the application of permethrin over time (non-significant double interaction trimming treatment \times insecticide treatment; $F = 0.49$, $p = 0.74$ and triple interaction trimming treatment \times insecticide treatment \times time interactions; $F = 0.61$, $p = 0.84$).

Three sequential, weekly applications of permethrin significantly ($F = 7.93$; $p < 0.001$) decreased the proportion of capitula infested by *Eucosma* 22 days after the first application (Figure 2). By 36 days

after the initial permethrin application, treated plants had one third of the frequency of infested heads as the control plants ($F = 67.68$; $p < 0.001$).

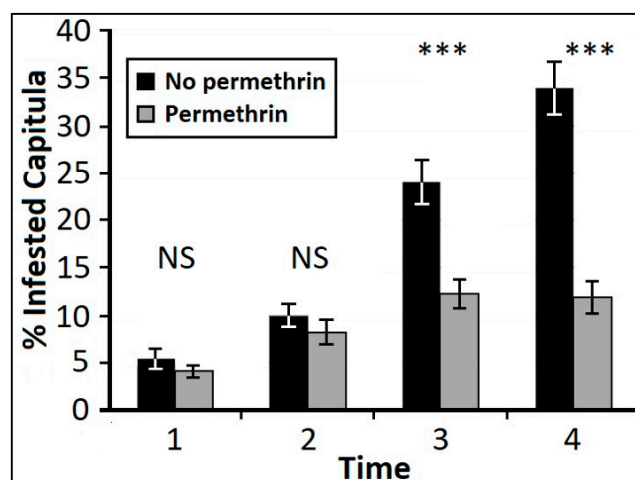


Figure 2. Percentage of heads infested with at least one *Eucosma* larva in *Silphium integrifolium* capitula treated with permethrin and control (no permethrin). All trimming treatments were pooled together since no differences were found between them in the response to permethrin. The insecticide was applied at times 1, 2 and 3. Time 1 = 23 July; 2 = 1 August; 3 = 15 August and 4 = 29 August. Error bars denote standard error. $N = 96$. *** $p < 0,001$. NS = non-significant

4. Discussion

4.1. Can Silflower Be Used as a Fodder?

Silphium perfoliatum (cup plant) was considered as animal fodder during the 1980s and 1990s. This species can be harvested once or twice a year in Europe, typically in June and September. The evaluation concluded that cup plant can yield up to 15 Mg ha^{-1} (dry matter) with a high fiber content that typically slows digestion [14]. Despite the economic importance of this forage and bioenergy crop in Germany (2000 ha in 2017), there are no previous reports on *S. integrifolium* or other *Silphium* species. On-farm production of hay and high-protein-content feed could present several advantages, among which are the diversification of crop cultivation and crop rotations, reduced consumption of feed concentrates transported over long distances and, when perennial crops are grown, a reduction in runoff during the winter season [43].

In our experiments we found that a pre-flowering harvest of *Silphium integrifolium* can produce excellent quality fodder, which is high in protein (14–18%) and comparable to alfalfa in terms of total N content. Silflower digestible fiber content indicates a higher digestibility and thus energy intake than alfalfa (25–40%) with a higher intake due to the low cellulose values. The overall RFV (a forage quality term that is used to rank forages) of silflower forage was between 2.5- and fourfold that of full-bloom alfalfa hay (100). These are very promising data in terms of forage quality and potential use for feeding cattle. The ensilage of the cut biomass also resulted in a high-quality feed, comparable to that of sorghum, with a higher crude protein content (9.6 vs. 6.6%), similar digestibility (ADF 41–42%), and higher predicted intake (aNDF 54 vs. 63%) because of the lower content of cellulose, hemicellulose and lignin. Our silage experiments relied on naturally occurring lactic bacteria and did not include the addition of commercial cultures of *Lactobacillum*, which usually include several species to improve efficiency [44]. The addition of these bacteria could further improve the transformation of soluble sugars into lactic acid, and should be tested. Questions also remain as to how much total biomass can be harvested under date and fertilization regimes designed to optimize biomass, and how harvest intensity can affect subsequent biomass production and carbohydrate storage.

4.2. Can Silflower Be Used as a Dual-Purpose Crop?

Two factors have been identified as critical for the development of a dual-purpose crop: (A) identification of the stalk elongation stage in which biomass should be harvested, in order to avoid undesirable tradeoffs between forage and seed-yield [45,46]; (B) matching crop phenology to environment, because delaying flowering outside the optimal period has profound negative consequences on grain productivity [47]. Within the sunflower family, the timing of trimming is critical because pre-anthesis conditions affect the growth of floral ovaries, which will become the pericarp of the grains after pollination [48]. The manipulation of plant source: sink relations might result in paying seed yield penalties such as those found in annual sunflower, in which a reduction in the source of assimilates before flowering decreased grain yields by 20–30% [48,49]. Our results indicate that a tradeoff between source availability (proxied by the amount of biomass removal with harvest) and grain production occurs in silflower as well. Harvesting biomass in late spring, when plants were approximately 60 cm in height provided a good quantity of excellent quality biomass for feed uses. However, the delay in phenology provoked by trimming shortened the reproductive season and greatly affected the number of capitula produced, resulting in a seed yield penalty of about 45%. Added to this tradeoff, removal of biomass might have consequences for carbohydrate storage in the crown, which is needed for next season regrowth, as found in other perennial oilseed crops [50,51].

Tradeoffs between biomass and seed production might be mediated by crown storage capacity, a key carbon source in perennials, which is not generally considered when dealing with annual crops. The re-sprouting of trimmed plants may deplete C and N stores in the crown, changing the source–sink ratio and therefore the hierarchy of allocation to reproduction. Consequently, carbon assimilation would be allocated to storage organs instead of seeds. This hypothesis needs to be tested in future experiments.

We did not test forage yield or quality after seed harvest at the end of the summer, because the stalks appear very fibrous and unpalatable at this stage. Still, these stalks have been cut, bailed and used by local farmers in Patagonia, in small trials for winter cow maintenance (Vilela 2019, personal communication). Potentially, some use could be made of this post-harvest residue as solid fuel [52]. Still, two forage harvests in one growth cycle (spring and fall) may have undesirable consequences for carbohydrate accumulation and nitrogen retranslocation to overwintering crowns.

Although the results of our study do not support the proposal that *Silphium integrifolium* could be profitably harvested for both high quality forage and as an oilseed grain in the same season, they support the possibility of developing a strategy of a forage–grain cropping system rotation without replanting. In this novel form of rotation, the same plants are harvested in late spring as forage in some years, or, bypass the biomass harvest and allow flowering and grain production in other years. The decision of harvesting biomass or grain would depend on fodder and oilseed prices and individual farmers' needs. In addition to offering flexibility to respond quickly to changes in the relative price of forage vs. oilseeds, weather, and machinery/labor availability, this kind of rotation provides the opportunity to prevent the buildup of populations of specialist insects or diseases.

4.3. Do Delays in Crop Phenology Reduce Insect Damage?

New methods for crop protection are needed that better mobilize the ecological processes of the natural regulation of crop pests, so as to reduce the dependence of agricultural systems on pesticides [30]. In an attempt to find a different approach to the conventional symptomatic treatment at the plot scale, we harvested aboveground biomass at different heights and moments. As a result, we were able to change the plant architecture and delay flowering.

Altering the planting date has been recognized for almost 30 years as a pest management practice for annual sunflowers [25]. Since silflower is a perennial mostly flowering on the second year, harvesting the stalks at pre-flowering was our only alternative to shift the flowering phenology a few weeks forward. Our data showed that harvesting stalks to delay flowering did not effectively reduce *Eucosma giganteana* colonization of flower heads. This suggests that the use of chemicals or

complete field harvest (thus eliminating flowers) may be necessary for the effective management of this specialist pest.

Breaking the life cycle of seed/head parasites may be particularly important for crop stands normally harvested for seed production. Adult insects lay eggs on flower heads and the larvae mature inside these structures. Harvesting plants for forage before the flower heads mature could kill the larvae before they reach the soil where they overwinter. Conversely, we have observed increased fungal pathogen severity on *Silphium* leaves and stalks regrowing in early summer after spring biomass harvest compared with older, unharvested leaves and stalks (Van Tassel, unpublished observation). Young leaves and stalks appear more tender than older ones, yet are immediately exposed to warm conditions in which pathogens thrive. Therefore, “rotation” to seed production could help reduce pathogen populations in crop stands normally harvested for forage. In this situation, occasional seed production may also be needed for replanting or to expand the acreage of *Silphium*.

5. Conclusions

Silphium integrifolium cannot be used as a dual crop during the same season, but it could be used in a special case of crop rotation where the same crop is harvested for forage and grain in different years, offering flexibility to farmers. Rotation between forage and grain production may reduce the buildup of populations of specialist insects. However, for *Eucosma giganteana* control in seed production years, the use of an insecticide might be necessary. Yield stability (forage and seed) across years remains unclear and requires further investigation.

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