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Leaf litter decomposition and nutrient release characteristics of several willow varieties within short-rotation coppice plantations in Saskatchewan, Canada --Manuscript Draft--

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Leaf litter decomposition and nutrient release characteristics of several willow varieties within short-rotation coppice plantations in Saskatchewan, Canada.

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Key Words: decomposition limit value, decomposition rate constant, principal component analysis, *Salix*, specific leaf area

Abbreviations: **k_{Biomass}**, decomposition rate constant; **k_{Nutrient}**, nutrient release rate constant; **LV_{Biomass}**, decomposition limit value; **LV_{Nutrient}**, nutrient release limit value; **PCA**, principal component analysis; **SE**, standard error; **SLA**, specific leaf area; **SRC**, short-rotation coppice

Abstract

Quantifying short-rotation coppice (SRC) willow leaf litter dynamics will improve our understanding of carbon (C) sequestration and nutrient cycling potentials within these biomass energy plantations and provide valuable data for model validation. The objective of this study was to quantify the decomposition rate constants (**k_{Biomass}**) and decomposition limit values (**LV_{Biomass}**), along with associated release rates (**k_{Nutrient}**) and release limits (**LV_{Nutrient}**) of nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca), and magnesium (Mg) of leaf litter from several native and exotic willow varieties during an initial four-year rotation at four sites within Saskatchewan, Canada. The **k_{Biomass}**, **LV_{Biomass}**, **k_{Nutrient}**, and **LV_{Nutrient}** values varied among the willow varieties, sites, and nutrients, with average values of 1.7 year⁻¹, 79 %, 0.9 year⁻¹, and 83 %, respectively. Tissue N had the smallest **k_{Nutrient}** and **LV_{Nutrient}** values, while tissue K and Mg had the largest **k_{Nutrient}** and **LV_{Nutrient}** values, respectively. The leaf litter production varied among willow varieties and sites with an average biomass accumulation of 7.4 Mg ha⁻¹ after the four-year rotation and associated C sequestration rate of 0.2 Mg C ha⁻¹ yr⁻¹. The average contribution of nutrients released from leaf litter decomposition during the four-year rotation to the plant available soil nutrient pool across varieties and sites was 22, 4, 47, 10, 112, and 18 kg ha⁻¹ of N, P, K, S, Ca, and Mg, respectively. Principal component analysis identified numerous

key relationships between the measured soil, plant tissue, climate and microclimate variables and observed willow leaf litter decomposition and nutrient release characteristics. Our findings support the contention that SRC willow leaf litter is capable of enhancing both soil organic C levels and supplementing soil nutrient availability over time.

Introduction

There is interest worldwide in developing renewable energy sources that can provide solid, liquid, and gaseous fuels through a variety of conversion technologies. Despite supplying less than 15 % of the world's primary energy, biomass energy is the largest renewable contributor to global primary energy supply and is expected to represent more than half of the near-term potential for expanding renewable energy [34,68]. The potential for biomass feedstock to substitute contemporary fossil fuel energy (and its derivatives) on many levels ensures that biomass energy will have a progressively important and sustained role within the growing bioenergy sector and associated bioproduct markets in the foreseeable future [17,51].

Numerous studies have quantified different social, economic, energetic, and environmental benefits attendant with establishing short-rotation coppice (SRC) willow biomass energy plantations to help achieve renewable energy commitments. For example, compared with first-generation bioenergy crops, SRC willow has been found to: enhance soil quality [15,40]; reduce soil erosion [38,52]; improve water quality by decreasing nitrogen (N) and phosphorus (P) losses via leaching and surface runoff [14,56]; encourage plant, animal, invertebrate, amphibian, and reptile biodiversity [7,53]; require less maintenance and agrochemical inputs [23,37]; provide higher biomass yield and greater potential for future production cost reductions [19,58]; and, stimulate rural economic development [1,70]. Additionally, compared to both first-generation bioenergy crops and other second generation herbaceous bioenergy crops (e.g., giant reed grass, Miscanthus, switchgrass, etc.), SRC willow production is reported to have a greater net energy ratio [16,17] and lower net greenhouse gas emissions [17,52], which is primarily attributed to its relatively low fertilization requirement.

The relatively low nutrient-demanding nature of SRC willow is partly due to the efficient nutrient cycling within these plantations. For instance, substantial nutrients are contained within leaf litter biomass; thereby, providing a long-term supply of mineralizable nutrients that satisfies a substantial portion of its annual growth demand [21]. Considering the effect fertilization

practices have on the economic [27,42], energetic [16,52], and environmental [5,16] facets of SRC willow production, it is important to quantify the decomposition rate and concomitant nutrient-release characteristics of willow leaf litter, in order to support the development of soil fertility management strategies that optimize fertilizer amendments needed to maximize biomass production [61,62]. Quantifying the contribution of leaf litter nutrient cycling to the soil nutrient budgets of essential plant nutrients is required to accurately forecast SRC willow plantation sustainability and the necessity of nutritional amendments [25]. Moreover, increased concern over rising atmospheric CO₂ concentration has prompted efforts to increase terrestrial carbon (C) sinks and, therefore, the decomposition rate constant (k_{Biomass}) for willow leaf litter is needed to improve the calculated C sequestration potential of SRC willow plantations [11,54].

The well-established key abiotic and biotic factors affecting leaf litter decomposition rate are climate, leaf litter quality, inherent soil fertility, and the decomposer community composition and activity [10]. Strictly considering the decomposition rate, however, does not completely define the entire decay process, as C storage and nutrient release characteristics are ultimately governed by the maximum decomposition limit of the leaf litter, thus defining its decomposition limit value [i.e., % of leaf litter mass loss when decomposition ceases; LV_{Biomass} ; 8,48]. Estimating LV_{Biomass} values for accumulated leaf litter mass loss during decomposition, using asymptotic functions, is a reliable indicator of the relatively stable fraction of residual organic matter that will cease to play a role in C dynamics and nutrient cycling under existing environmental conditions [8]. The limit value principle is one of several methods (e.g., historic soil inventories, chronosequences, N-balance method, and dynamic process-oriented models) that can be used to estimate soil C accumulation over time [43]. In order to quantify the leaf litter dynamics of several willow varieties, a litter bag experiment was replicated at four different sites across a 500 km north-south pedoclimatic gradient in Saskatchewan, Canada, covering a variety of soil types and climatic conditions. The objective of this study was to quantify the k_{Biomass} and LV_{Biomass} values, and associated release rates (k_{Nutrient}) and release limits (LV_{Nutrient}) of N, P, potassium (K), sulphur (S), calcium (Ca), and magnesium (Mg) of leaf litter from several exotic willow varieties, along with a native willow variety for comparison, within SRC willow plantations during the initial four-year rotation, to provide insight into the relevance of leaf litter nutrient additions into the plant available soil nutrient pool. We hypothesized that leaf litter mass loss and nutrient release characteristics would vary according to specific nutrient,

willow variety, and site as related to the soil and environmental conditions. Although the essential role annual leaf litter additions play in augmenting soil organic C levels [40,54] and nutrient cycling [13,20] within SRC willow plantations has been previously recognized, to our knowledge, no LV_{Biomass} , k_{Biomass} , k_{Nutrient} , or LV_{Nutrient} values have been developed for any *Salix* spp. leaf litter. Assessing willow leaf litter dynamics will help to improve our understanding of C sequestration and nutrient cycling efficiency within SRC willow plantations, while providing valuable data for validating dynamic process-oriented biogeochemical models [3,18].

Materials and Methods

Study sites and willow varieties

The data for this study were collected from four SRC willow variety trial plantations located along a 500 km north-south pedoclimatic gradient within Saskatchewan, Canada, from the south-east corner of the province to the southern boundary of the boreal forest in the central area of the province. The selected sites represent the diverse soil types and climatic conditions existing in the province (Fig. 1 and Tables 1 and 2). At each of the four sites, a single pedon was excavated and a full soil taxonomic assignment given to classify the soils according to the Canadian System of Soil Classification [63]. The following replicated variety trial information was originally reported in Hangs et al. [26]. In the spring of 2007, six willow varieties, developed by the SUNY-ESF breeding program, were planted at each site in a randomized complete block design ($n = 4$) adapted from the protocols of Abrahamson et al. [2]. The willow varieties used were: Allegany (*Salix purpurea*), Canastota (*Salix sachalinensis* \times *miyabeana*), Fish Creek (*Salix purpurea*), Sherburne (*Salix sachalinensis* \times *miyabeana*), SX61 (*Salix sachalinensis*), and SX64 (*Salix miyabeana*). Each varietal plot (6.3×7.8 m) consisted of 78 plants (three double-rows of 13 plants row⁻¹), with spacings of 1.5 m between the double-rows, 60 cm between rows within the double-row, and 60 cm between plants within the double-row; resulting in a planting density of approximately 15,873 plants ha⁻¹. In the spring of 2008, the willow plants were coppiced and grown for an additional three years before harvesting. Pre- and post-planting site preparation to control non-crop vegetation included both mechanical (deep tillage, light cultivation, tandem disc, mowing, and hand weeding) and chemical (Goal™ 2XL, 2 L ha⁻¹; Roundup WeatherMax®, 2 L ha⁻¹; Simazine 480, 4.7 L ha⁻¹; Pardner®, 0.5 L ha⁻¹) treatments. Stem counts, heights, and diameters (at 30 cm height) of the central 18 stools within each varietal plot were assessed after

1 each growing season. Stem basal area was calculated on an individual stem basis and
2 extrapolated to a stand level based on stem density measurements.

3 *Measuring soil nutrient availability*

4 After planting the willow at each site, three 60 cm depth soil cores were collected within each
5 varietal plot using a JMC backsaver probe (Model PN001; Clements Assoc. Inc, Newton, IA,
6 USA), separated into 10 cm depth increments, and composited. All soil samples were air-dried
7 to a constant weight, ground with a rolling pin to break aggregates, mixed, sieved (< 2 mm
8 fraction retained), and analyzed for extractable nutrient levels (N, P, K, S, Ca, and Mg), total and
9 organic N, total P, organic and inorganic C, pH, and EC. Total inorganic N (NH_4^+ -N and NO_3^- -
10 N) and inorganic P were determined using 2.0M KCl [41] and modified Kelowna [50]
11 extractions, respectively, with the extracts analyzed colorimetrically (Technicon AutoAnalyzer;
12 Technicon Industrial Systems, Tarrytown, NY, USA). Extractable S was determined using
13 0.01M CaCl_2 [31] and analyzed using microwave plasma-atomic emission spectrometry (4100
14 MP-AES; Agilent technologies, Melbourne, Australia). Extractable K, Ca, and Mg were
15 determined using 1.0M NH_4OAc [29] and analyzed using either atomic emission (K) or
16 absorption (Ca and Mg) spectroscopy (Varian Spectra 220 Atomic Absorption Spectrometer;
17 Varian Inc., Palo Alto, CA, USA). Total N was determined using a $\text{H}_2\text{SO}_4/\text{H}_2\text{O}_2$ digest [65] and
18 analyzed colorimetrically as well. Organic N was calculated from the difference between total N
19 and inorganic N. Soil organic C (SOC) was measured using a LECO C632 Carbon Analyzer
20 [LECO Corporation, St. Joseph, MI, USA; 71], following a 6 % H_2SO_3 pre-treatment to remove
21 the inorganic C [59]. Soil pH and EC [1:2 soil suspension; soil:water on a weight basis; 28]
22 were analyzed using a Beckman 50 pH Meter (Beckman Coulter, Fullerton, CA, USA) and an
23 Accumet AP85 pH/EC meter (Accumet, Hudson, MA, USA), respectively. Particle size
24 distribution was determined using a Horiba LA-950 Particle Size Distribution Analyzer (Horiba
25 Instruments Inc., Irving, CA, USA) after pre-treatment with bleach (sodium hypochlorite) to
26 remove organic matter, followed by a 10 % solution of sodium hexametaphosphate to breakdown
27 clay aggregates.

Leaf litter production and nutrient content

Total leaf biomass for each willow variety was estimated annually at each site throughout the four-year rotation by collecting all of the leaves from three stems (representing the average size) within each plot in early September and extrapolating the leaf biomass to a stand level based on stem density measurements. Using this leaf biomass as a proxy is a more accurate estimation of stand level leaf litter biomass, compared to that estimated from litterfall traps placed randomly underneath the canopy, considering the assumption that absolute leaf fall is inevitable with deciduous species growing in temperate climates. In a companion study, we collected fifty abscising leaves throughout the canopy from each varietal plot every November for estimating the nutrient resorption efficiency [% of initial nutrients resorbed during leaf senescence; 73] prior to leaf abscission. The associated foliar nutrient mass loss during leaf senescence was used to correct the estimated stand level leaf biomass from September. Beyond mass loss due to nutrient retranslocation, the % initial mass loss during leaf senescence was assumed to be minor [12]. Estimates of accumulated leaf litter nutrients throughout the four-year rotation were then determined by multiplying the nutrient concentrations of abscising leaves collected in November by the corrected total leaf biomass estimates from September. The September and November leaves were dried at 65°C to a constant weight, thoroughly milled and homogenized prior to analyses, and their total N, P, K, Ca, and Mg concentrations were analytically measured following a H₂SO₄/H₂O₂ digest [65] as previously described. Total S was measured using a TruSpec CNS analyzer (Leco Corporation, St. Joseph, MI, USA). Prior to drying the September leaves, the total leaf area was determined using a leaf surface area meter (LI3100; LI-COR Inc., Lincoln, NE).

Leaf litter decomposition

Litterbags were used to measure the rate of decomposition and nutrient release of the willow leaf litter throughout the rotation. At the end of the establishment year (i.e., prior to coppicing), senesced and abscising leaves were collected in November from each varietal plot at every site. For comparison purposes, abscising leaves from a native willow species (*S. eriocephala*) collected from wetlands near Indian Head, SK, Canada (UTM coordinates:13U 593345 5596906) were also included at each site. The specific leaf area [SLA, cm² g⁻¹; 64] of the

November leaves used in the leaf litter bags was determined using a leaf surface area meter (LI-3100; LI-COR Inc., Lincoln, NE). All intact leaves were then dried at 65°C to a constant weight, and a 5 g subsample placed in a polyethylene screen bag (20 × 20 cm; 1 mm mesh) and stapled closed. Triplicate litterbags were placed on the soil surface within their respective varietal plots prior to snowfall, with a single randomly chosen litterbag removed from each plot every 12 months over the subsequent three years. Analyzing several litter bags from within each plot (spread out to help account for micro-scale variability, but using their mean value for the statistical analyses) annually would have been ideal; however, we were logistically limited to one litter bag per plot each year. Our assumption was that any micro-scale variability would be accounted for by placing the three litter bags randomly throughout each replicate plot. All residual leaf litter was dried at 65°C to a constant weight, weighed to determine mass loss, and along with subsamples of the original leaf litter material (i.e., time = 0), were prepared and analyzed for their N, P, K, S, Ca, and Mg concentrations, as previously described, to estimate the nutrient release rates from the decomposing leaf litter throughout the rotation. For each willow variety, its k_{Biomass} and LV_{Biomass} values were determined at every site by fitting the proportion of litter remaining in the litter bag each year to the following asymptotic decomposition model (Eq. 1) using nonlinear modelling in JMP 10 (Version 10; SAS Institute, Cary, NC) following the protocols of Hobbie et al. [30]

$$X = A + [1 - A]e^{-k_{\text{Biomass}}t} \quad (1)$$

where X is the proportion of initial leaf litter mass remaining at time t and assumes that a recalcitrant fraction (A ; asymptote) of the initial leaf litter biomass possesses a decomposition rate so slow that it is practically zero, while another fraction ($1 - A$) decomposes exponentially at rate k_{Biomass} . Although the model allows for complete litter decomposition (i.e., $A = 0$), a portion of leaf litter normally reaches a stage of relative stability, where further degradation of residual near-humus material is negligible under existing environmental conditions [10], especially during the comparatively short time frame of a SRC willow production system (i.e., 22 years; seven three-year rotations). The LV_{Biomass} value (%) is then calculated as $1 - A \times 100$. A similar approach was used to model nutrient release from decomposing leaf litter. However, due to inconsistent model convergence among nutrients using the asymptotic model, the single

exponential model was used to estimate k_{Nutrient} values from the different varietal leaf litters at every site using Eq. 2, a simplified equation adapted from Olson [46]:

$$-k_{\text{Nutrient}} = \frac{\ln\left(\frac{X_i}{X_0}\right)}{t} \quad (2)$$

where X_0 is initial nutrient content within the leaf litter and X_i is the nutrient content remaining at collection time (t) in years. This model assumes complete nutrient release over time, but given the observed asymptotic form of nutrient release after three years, which was consistent among willow varieties and sites (data not shown), we felt that it was acceptable to consider the proportion of initial nutrients released from the leaf litter after the incubation to represent the nutrient release limit value (i.e., LV_{Nutrient} ; %), with the remaining nutrients essentially immobilized.

A well-documented shortcoming of litterbag studies is the contamination of decomposing leaf material with non-target organic or inorganic material (e.g., earthworm casts, fungal hyphae, weed litter, and soil) over time. In this study, the primary contaminant at each site was soil, which was easily removed by blowing the litter bags using pressured air. An exception to this, however, occurred after three years at Saskatoon where the heavy clay soil was intimately bound with the small leaf litter residue, which rendered the air treatment ineffective. Such difficulty with clay soil has been reported elsewhere and is typically accepted as unavoidable and not corrected for [62]. We corrected for the soil contamination by determining the proportion of residual mineral material following the $\text{H}_2\text{SO}_4/\text{H}_2\text{O}_2$ digest and multiplying its weight by the nutrient concentration of the plot-specific soil (0-10 cm) analyses to estimate the topsoil nutrient contribution to the contaminated leaf sample. For example, a leaf litter digest sample having 20 mg g^{-1} total N, but with 50 % soil contamination (having a 3 mg g^{-1} soil N content), would require a -0.15 % N correction (i.e., $0.5 \times 0.003 \times 100$), resulting in only 1.85 % N (93 % of the total N in the sample) attributable to leaf litter N. Using the estimated k_{Nutrient} and accumulated leaf litter biomass over the four-year rotation, we calculated the contribution of leaf litter nutrient release to the plant available soil nutrient pool. The leaf litter cohorts considered in the calculations for nutrient cycling during the rotation were three years of establishment year leaf litter (i.e., pre-coppice leaf biomass), two years of nutrient release from the first year post-

coppice leaf litter, and one year of nutrient release from the second year post-coppice leaf litter. Given that the willow was harvested three years after coppicing, the remaining nutrient release contributions from the first to third year post-coppice leaf litter would be associated with the second rotation.

Meteorological conditions during incubation period

A Campbell Scientific CR10X (Campbell Scientific Inc., Edmonton, AB, Canada) was used at each site to monitor air temperature, rainfall, relative humidity, and wind speed throughout the study. Soil temperature (0-60 cm) was also assessed. Potential evapotranspiration [66] and Aridity Index [69] were estimated annually for each site using the measured climate data. Accumulated snow depth was measured at each site annually in February. The beginning and ending of each growing season was determined using a 5 °C baseline mean daily temperature, sustained or unsustained for at least five consecutive days, respectively, using both air and soil temperatures for comparison. Growing season length was calculated annually in this manner.

Statistical analyses

Means comparisons of measured variables were performed using least significant differences (LSD; Tukey-Kramer's method of multiple comparison) at a significance level of 0.05 using PROC MIXED in SAS [39; version 9.2; SAS Institute Inc., Cary, NC, USA], with groupings performed with the pdmix800 SAS macro [55]. The effects of variety were considered fixed, while those of site and replicate (nested within site) were considered random. Normality of distributions (PROC UNIVARIATE) and homogeneity of variances (Bartlett's test) of all data sets were verified, and when required, the data were Log₁₀ transformed prior to analysis. A principal component analysis (PCA) was performed using JMP 10 (Version 10; SAS Institute, Cary, NC, USA) to investigate the relationship between all estimated leaf litter decomposition and nutrient release variables and relevant soil and plant tissue characteristics measured at each site. An additional PCA was performed using the measured climatic data at each site and site averages of different willow canopy variables (e.g., total leaf surface area, average stem basal area, and average stem height), which were considered surrogate measures of microclimate effect, along with estimated leaf litter decomposition and nutrient release variables during the incubation period. Correlation strength among variables is indicated by the cosine of the angle

1 between variable vectors and variable groupings were arbitrarily based on an angle of 30° (i.e., R
2 = 0.87). Vectors of directly and indirectly correlated variables point in the same or opposite
3 direction, respectively, whereas uncorrelated variables have vectors at right angles to each other.

4 **Results**

5 *Leaf litter production and nutrient content*

6 The leaf litter production varied among the willow varieties and sites with an average
7 accumulation of 7.4 Mg ha⁻¹ after the initial four-year rotation (Table 3). Annual leaf litter
8 biomass increased each year for all varieties and sites with 0.2, 1.5, 2.1, and 3.3 Mg ha⁻¹
9 produced on average each year, respectively (data not shown). With the exception of Fish Creek,
10 there were no significant differences ($P > 0.05$) in cumulative leaf litter biomass after four years
11 among the six varieties, with the lowest leaf litter production at Saskatoon compared to the other
12 three sites (Table 3). There was a 50 % greater variation in leaf litter biomass compared to
13 nutrient concentration among varieties and sites (data not shown). There was a strong
14 relationship ($R^2 = 0.64$ -1.00; $P < 0.05$; data not shown) between leaf litter biomass production
15 throughout the rotation and leaf litter nutrient accumulation regardless of variety, site, or year.
16 The average leaf litter nutrient content among willow varieties and sites was 83, 15, 115, 26,
17 264, and 43 kg ha⁻¹ of N, P, K, S, Ca, and Mg, respectively (Table 3). The leaf litter N, P, and
18 Mg contents were not significantly different ($P > 0.05$) among varieties. Generally, for the
19 remaining nutrients and when comparing leaf litter nutrient content among sites, there was a
20 trend of increasing nutrient content with increasing leaf litter biomass. For example, the
21 Saskatoon site had significantly lower nutrient content because of its low biomass, whereas
22 Estevan had significantly higher biomass and nutrient content (Table 3). There were strong
23 relationships ($R^2 = 0.64$ to 1.00; $P < 0.05$; data not shown) between leaf litter biomass production
24 throughout the rotation and leaf litter nutrient accumulation regardless of variety, site, or year.
25 Exceptions to this were observed with the P and Mg contents of Estevan and Prince Albert leaf
26 litter, respectively (Table 3). The average (SE) initial nutrient concentrations of native leaf litter
27 were 17.2 (0.7), 2.5 (0.1), 4.1 (0.1), 2.3 (0.3), 50.4 (8.3), and 20.5 (3.8) mg g⁻¹ N, P, K, S, Ca,
28 and Mg, respectively, compared to 13.1 (0.4), 1.5 (0.1), 12.1 (0.8), 3.3 (0.1), 66.9 (2.3), and 13.2
29 (1.0) mg g⁻¹ N, P, K, S, Ca, and Mg, respectively, for the six exotic willow varieties (data not
30 shown).

Leaf litter decomposition and nutrient release

The average leaf litter k_{Biomass} , LV_{Biomass} , and A values for the one native and six exotic willow varieties across the sites were 1.7 year^{-1} , 78.9 %, and 0.21, respectively (Table 4). The estimated k_{Biomass} and A were 28 and 40 % greater at Prince Albert, respectively, but with an LV_{Biomass} 11 % smaller compared to the other sites. The average leaf litter mass loss was 62 % (i.e., 38 % of the initial mass remaining) after the first year across all varieties and sites (Fig. 2). The average (SE) k_{Nutrient} values across all varieties and sites, were 0.45 (0.02), 0.69 (0.02), 1.13 (0.04), 0.91 (0.04), 1.00 (0.04), and 1.07 (0.04) for N, P, K, S, Ca, and Mg, respectively (Table 5). The k_{Nutrient} values differed among the seven willow varieties examined, with Fish Creek and Sherburne consistently having the largest and smallest values (averaging 1.2 and 0.6 year^{-1} , respectively) across the different nutrients and sites (Table 5). Specifically, nutrients were released 56 % faster from Fish Creek leaf litter and 40 % slower from Sherburne leaf litter, compared to the other varieties. With the exception of K and Mg, the leaf litter at Estevan released its nutrients faster than the other sites; conversely, the decomposing leaf litter at Prince Albert had the slowest nutrient release rate, except for K and Mg, which was fastest. Relative to the initial leaf litter nutrient contents, the average (SE) release of N, P, K, S, Ca, and Mg after the first year across all varieties and sites was 36 (2), 51 (2), 69 (1), 61 (2), 63 (2), and 61 (2) %, respectively (Fig. 3). The trend in k_{Nutrient} values among varieties and sites was similar to the LV_{Nutrient} values observed, resulting in a strong relationship ($R^2 = 0.82$; $P < 0.02$; data not shown) between the two variables. The LV_{Nutrient} values differed among varieties, sites, and nutrients during the rotation with average values of 75, 83, 86, 82, 84, and 89 % for N, P, K, S, Ca, and Mg, respectively, across varieties and sites (Table 6). The LV_{Nutrient} values were similar among all six exotic varieties (i.e., $CV < 5 \%$), but approximately 20 % smaller for the native variety leaf litter over the incubation period. The LV_{Nutrient} values at Prince Albert were 26, 16, 12, and 10 % smaller for N, P, S, and Ca respectively, compared to the other three sites, but had the largest LV_{Nutrient} values for K and Mg (Table 6). The k_N and LV_N values were 53 and 12 % smaller, respectively, compared to the average values of other nutrients (Tables 5 and 6). Using the estimated k_{Nutrient} and leaf litter biomass accumulation values, the average contribution of nutrients released from leaf litter decomposition during the four-year rotation to the plant

1 available soil nutrient pool across varieties and sites was 22, 4, 47, 10, 112, and 19 kg ha⁻¹ of N,
2 P, K, S, Ca, and Mg, respectively (Table 7).

3 *Principal Component Analysis*

4 The PCA ordination identified several distinct groupings among the measured soil, plant tissue,
5 climatic, and willow canopy properties associated with willow leaf litter decomposition and
6 nutrient release dynamics (Figs. 4 and 5). Specifically, variable clustering clearly indicated:
7 SLA and soil C:N were the primary variables directly related to k_{Biomass} ; initial leaf litter nutrient
8 concentrations (i.e., litter quality) were directly linked with the k_{Nutrient} values; and soil nutrient
9 availability was directly correlated to the LV_{Biomass} and LV_{Nutrient} values (Fig. 4). Additionally, a
10 second PCA incorporating climate and canopy data revealed: the first year climate (e.g., annual
11 and growing season rainfall and snowfall, relative humidity, and growing season length) and
12 willow canopy variables (e.g., stem height, leaf surface area, and stem basal area) were more
13 closely related to k_{Biomass} than second and third year conditions; climatic variables indicating less
14 moisture availability at the soil surface (e.g., annual air temperature, aridity index, wind speed,
15 and potential evapotranspiration) were indirectly related to k_{Biomass} ; increased moisture
16 conditions were associated with increased k_{Nutrient} values of K and Mg; and, there was a stronger
17 relationship between growing season length based on soil temperature data and k_{Biomass} compared
18 to growing season length derived from air temperature data and k_{Biomass} (Fig. 5).

19 **Discussion**

20 *Leaf litter production and nutrient content*

21 The estimated leaf litter biomass accumulated during the initial four-year rotation and its nutrient
22 concentrations are within the range reported in the literature ([36,54] and [61,62], respectively).
23 The greater variation in leaf litter biomass compared to nutrient concentration among varieties
24 and sites indicates that varying biomass production was primarily responsible for the observed
25 differences in leaf litter nutrient content and helps to explain the expected strong direct
26 relationship between leaf litter biomass production and leaf litter nutrient accumulation. For
27 example, the smallest leaf litter nutrient sink at Saskatoon was consistent with its reduced leaf
28 production compared to the other sites. Notable exceptions to this trend were the leaf litter P

content at Estevan and leaf litter Mg content at Prince Albert (Table 3). These observed deviations are explained by differences in foliar nutrient concentrations, due to the contrasting soil P and Mg availability at these two sites (Table 2). Specifically, Estevan and Prince Albert had the lowest measured soil P and Mg levels, respectively, while repeated fertilizer P applications at Prince Albert prior to plantation establishment lead to high residual soil P, resulting in apparent enhanced P uptake by the willow varieties growing at Prince Albert and resultant larger leaf litter P sink over time.

Leaf litter decomposition

The estimated k_{Biomass} and LV_{Biomass} values of the different willow variety leaf litter across the four sites were within the range reported for deciduous species [10]. Varietal differences in leaf litter decomposition as observed in this study have also been reported for *Salix* spp. elsewhere [61,62]. The strong inverse relationship between k_{Biomass} and LV_{Biomass} observed for all varieties and sites is consistent with the well-established understanding of leaf litter decomposition dynamics [9]. For example, the leaf litter at Prince Albert had the largest k_{Biomass} value, but the largest proportion of recalcitrant leaf litter (i.e., A value) and attendant lowest LV_{Biomass} value at the end of the incubation period compared to the other sites (Table 4). Increased leaf litter quality (i.e., high initial nutrient concentrations, especially N and P) typically supports an initially high decomposition rate over the short-term, but leads to a larger fraction of recalcitrant biomass remaining (i.e., decreased LV_{Biomass}). Consequently, there is often a negative correlation between initial leaf litter N concentrations with LV_{Biomass} [10] and this helps to explain the difference in LV_{Biomass} values between the native *S. eriocephala* leaf litter and exotic *Salix* varieties (Table 4 and Fig. 2).

During the early-stage of decomposition (< 1 year), the primary regulator of k_{Biomass} often is litter quality [i.e., macronutrient concentration; 10], but as decomposition proceeds and biomass is lost, the relative concentration of lignin increases and typically becomes the key factor controlling subsequent decomposition [8,61]. Furthermore, the relative enrichment of low-molecular weight N compounds within decomposing leaf litter can also inhibit decomposition by not only reacting with lignin to create more recalcitrant aromatic compounds, but also repressing ligninolytic enzymes production by soil fungi [8]. Similar leaf litter N enrichment was evident in our study after three-years. Namely, the leaf litter N content

decreased less over time among the varieties and sites compared to other nutrients (Fig. 3c) while leaf litter N concentration among the varieties increased 58, 14, 11, and 25 % at Prince Albert, Birch Hills, Saskatoon, and Estevan, respectively. The remaining nutrient concentrations decreased over time (data not shown), which is in agreement with other studies [33,61]. This marked increase in k_{Biomass} , coupled with leaf litter N enrichment (i.e., immobilization) observed at Prince Albert, is presumably due to a greater soil microbial response to the added leaf litter C source within the sandy soil having inherently poor fertility and less SOC [Table 2; 61]. The strong negative relationship between SOC level and k_{Biomass} across the four sites ($k_{\text{Biomass}} = -0.3244(\text{SOC}) + 2.3969$; $R^2 = 0.95$; $P < 0.05$) appears to support this assertion. Additionally, the largest C:N ratio of the coarse-textured Prince Albert soil helps to explain the enhanced leaf litter N enrichment, as the decomposer population would immobilize more N, resulting in 26 % less N released from the leaf litter after three years compared to the other sites (Table 6). The recalcitrant portion of annual leaf litter production is anticipated to accumulate over time, thus representing one mechanism whereby SRC willow plantations are capable of sequestering SOC. The smaller $\text{LV}_{\text{Biomass}}$ value at Prince Albert implies enhanced leaf litter accumulation compared to the other sites, which will be beneficial for this sandy soil. Undoubtedly, this is one of the mechanisms underlying the measured increase in SOC level following the introduction of SRC willow on sandy former agricultural soil that has been reported elsewhere [35,36].

Simply multiplying the varietal leaf litter production throughout the rotation by its corresponding A value (Tables 3 and 4), yields an estimated average rate of SOC sequestration from leaf litter of $0.21 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ (assuming a C fraction of 0.5) and falls within the range of recently reported estimates [36,54; 0.28 and $0.15 \text{ Mg C ha}^{-1} \text{ year}^{-1}$, respectively]. Contrary to herbaceous alternative bioenergy crops, which experience chronic removals of all above-ground biomass, the SRC willow plantations in this study cycled more than seven tonnes per hectare of leaf litter biomass on average prior to harvest (Table 3), which will play an important role not only in augmenting SOC levels, but also long-term nutrient cycling. Notwithstanding the substantial leaf litter nutrient additions to the soil surface, it is important to recognize that these nutrients are principally bound in the organic matter and consequently, are not readily available for plant uptake until mineralized.

Leaf litter nutrient release

The bulk release of leaf litter nutrients other than N (only approximately 1/3 released after the first year; Fig. 3c), concurs with previous studies [24,61]. The markedly smaller k_N value at Prince Albert is probably a function of greater leaf litter N immobilization by the decomposer community of the relatively poor soil (Table 2). Inorganic N from either leaf litter mineralization or fertilizer N has been shown to become rapidly immobilized within the stable soil organic N pool, especially in sandy soils, representing long-term N retention within SRC willow plantations [4,60]. Although some N, P, and S can be partially leached immediately after litter fall [10], observed differences in k_P and k_S values are likely due to greater microbial immobilization as well, while differences in k_K , k_{Ca} , and k_{Mg} values are typically associated with leaf litter leaching of these base cations, with less dependence on microbial-mediated release [47,61].

The observed differences in nutrient release among willow varieties and sites (Figs. 3a and 3b), along with differing CV of $k_{Nutrient}$ and $LV_{Nutrient}$ values (ranging from 9-38 % depending on the nutrient; Tables 5 and 6) are attributed primarily to the effect of differing soil nutrient availability on leaf litter quality (CV ranging from 31-74 % depending on the nutrient; data not shown) and the degree of nutrient immobilization during decomposition. Tissue nutrient concentration is a principal determinant of litter quality and a strong factor controlling litter decomposition rates and nutrient cycling [72]; although relative differences in lignin or tannin content are also important [57,61].

Knowledge of leaf litter nutrient release characteristics is useful when selecting varieties (e.g., Sherburne; Fig. 3a and Table 5) for use in environmentally sensitive areas (e.g., riparian zones) where enhanced nutrient immobilization (especially N and P) within leaf litter would be advantageous. Conversely, when the objective is to reduce fertilizer requirement for SRC willow production, using varieties (e.g., Fish Creek; Fig. 3a and Table 5) with leaf litter possessing quicker nutrient release characteristics would be beneficial, in order to satisfy a larger portion of the immediate nutritional demand naturally and more economically. Improving the synchrony between nutrient release from leaf litter and subsequent plant nutrient demand will enhance nutrient uptake efficiency by the willow while increasing nutrient retention in the system [45]. It is important to note that less than half of the nutrients immobilized within leaf

litter were released during the four-year rotation (Tables 2 and 7). Consequently, the majority of leaf litter nutrients will be available for willow uptake during the second rotation and such capacity of leaf litter nutrient cycling to support the nutritional requirements of subsequent rotations is well known [13,22,33].

Principal component analyses

Principal component analysis of soil and plant tissue properties associated with willow leaf litter decomposition and nutrient release variables (Fig. 4) visually supports our concept of the aforementioned inter-relationships, namely: i) the direct relationship between $LV_{Biomass}$ and soil nutrient availability (along with an indirect relationship with $k_{Biomass}$), with less influence of litter quality; ii) $k_{Nutrient}$ values were primarily controlled by litter quality, with relatively little influence of soil nutrient availability; iii) $k_{Nutrient}$ is directly related to $LV_{Nutrient}$, with the exception of Ca; iv) $LV_{Nutrient}$ values for N, P, and S are chiefly controlled by the availability of these soil nutrients, while $LV_{Nutrient}$ values for K and Mg was mainly dependant on initial litter contents; and, v) the direct relationship between SLA and $k_{Biomass}$. Strong positive correlations between SLA and $k_{Biomass}$ have been acknowledged previously, with smaller SLA values indicative of increased leaf thickness and density, which is associated with a physically tougher foliar structure and increased concentration of recalcitrant chemical constituents, such as lignin [32]. In our study, the native willow variety SLA was about half ($89.6 \text{ cm}^2 \text{ g}^{-1}$; SE 2.9) the average value for the six exotic willow varieties ($134.8 \text{ cm}^2 \text{ g}^{-1}$; SE 1.0), which helps to explain the measured differences in leaf litter dynamics observed in mass loss and nutrient release characteristics. Although strong relationships among these variables were identifiable with PCA, only 53.7% of the variability was accounted for in the two principal axes (Fig. 4), thus, indicating the need to include additional factors affecting leaf litter decomposition, particularly climatic variables.

Moore et al. [44] examined the three-year decomposition dynamics of 11 litter types across 18 sites throughout Canada and found annual precipitation to be strongly related to litter mass remaining. Likewise in our study, the relationship between climate and leaf litter decomposition was explicit, with 80.1% of the variability explained in the two principal axes (Fig. 5). Specifically, the strong direct relationship between first-year precipitation (growing season and annual rainfall and snowfall) and relative humidity with leaf litter mass loss and

nutrient (e.g., base cations) release, contrasted with the indirect relationship between climate variables attendant with less moisture availability at the soil surface (e.g., annual average air temperature, aridity index, wind speed, and potential evapotranspiration), indicates the prominent role climate (i.e., moisture availability) plays in controlling willow leaf litter decomposition and nutrient release dynamics in semi-arid Saskatchewan. Additionally, the closer relationship between first year climate conditions and k_{Biomass} and k_{Nutrient} agrees with the majority loss of leaf litter mass and nutrients during the first year (Fig. 3). Trofymow et al. [67] suggests that the first-year loss of soluble compounds (e.g., carbohydrates, phenolics, and tannins) largely control leaf litter mass loss during the first year and might be related to accumulated winter precipitation following leaf fall and proportional leaf litter leaching during snow melt in the subsequent spring. Their proposed role of subsequent snowfall following litterfall was corroborated in our study with the strong relationship between first-year snowfall and k_{Biomass} and k_{Nutrient} (Fig. 5). Although the effect of climate on leaf litter dynamics is well known, the degree of canopy cover can also regulate the understory microclimate [10], which was manifested in the strong relationship between the first-year surrogate measures of microclimate (e.g., leaf surface area, average stem height, and total basal area) and k_{Biomass} (Fig. 5).

Leaf litter lignin concentration data may have improved the PCA results, given its consistent control on decomposition across regional scales [44,67]. Additionally, considering the importance of soil flora and fauna populations within SRC willow plantations [6,49], including soil biota community structure and activity data among varieties and sites may have also enhanced the PCA results, given their vital relationship with leaf litter dynamics [48]. Although soil biota were not assessed in this study, their importance may be indicated indirectly by the closer relationship between calculated growing season length based on soil temperature (instead of air temperature) and k_{Biomass} (Fig. 5). Fluctuating air temperature would have less influence on soil biota, due to the ability of soil to buffer large diurnal changes in air temperature throughout the year. For example, the CV of measured air, soil (0-10 cm), and soil (0-60 cm) temperature across the four sites throughout the three-year incubation ranged from 428-1755, 105-144, and 108-129 %, respectively. Consequently, soil temperature appears to be a reliable variable for modelling willow leaf litter dynamics within temperate climates like Saskatchewan, presumably due to its close association with soil biota abundance and activity.

1 *Leaf litter nutrient cycling, long-term soil nutrient availability, and SRC willow plantation* 2 *sustainability*

3 Our estimates of leaf litter nutrient cycling are at the low end of available literature values [Table
4 7; e.g., 22]. These results are a function of not only the relatively low leaf production at our
5 plantations (Table 3), but also our values are estimates of actual nutrient additions to the plant
6 available soil nutrient pools, due to mineralization during the four-year rotation, as opposed to
7 leaf litter nutrients presumed to be entirely released eventually. Under Saskatchewan conditions,
8 however, assuming complete nutrient release would result in an overestimation of leaf litter
9 nutrient release from 5-44 % depending on willow variety, nutrient, and site (Table 6). Also, a
10 considerable portion of nutrients bound in the accumulated leaf litter during the four-year
11 rotation will not be released until the second rotation and perhaps beyond; therefore, these
12 nutrients were not included in our estimates (Tables 2 and 7). Regardless, our findings support
13 the contention that decomposing leaf litter is an important nutrient cycling mechanism helping to
14 satisfy the long-term nutritional demands of SRC willow plantations [22,33]. The significant (P
15 <0.05) variety \times site interaction effect on leaf litter nutrient additions was influenced more by the
16 differences in accumulated leaf litter biomass during the rotation, across the exotic varieties and
17 sites, than by variation in their leaf litter nutrient concentrations (CVs of 38 and 22 %, respectively;
18 data not shown). For example, the Saskatoon soil received 65 % less nutrient
19 contributions from leaf litter compared to the other sites (Table 7) and is primarily a function of
20 differences in biomass allocation (i.e., root growth favoured over leaf production) under the drier
21 growing season conditions at Saskatoon observed throughout the rotation.

22 **Conclusion**

23 Litterfall decomposition is a primary mechanism for C and nutrient cycling within most
24 terrestrial ecosystems and SRC willow plantations are certainly no exception. The estimated leaf
25 litter decomposition and nutrient release variables presented herein are the first reported values
26 for *Salix* spp. Modelling efforts aimed at estimating the climate change mitigation potential and
27 long-term sustainability of SRC willow plantations are highly dependent on reliable input
28 parameters; in particular, leaf litter decomposition data for predicting the magnitude of C
29 sequestration and nutrient release to forecast the potential need of supplemental nutrient
30 amendments. Contrary to herbaceous alternative bioenergy crops (e.g., giant reed grass,

Miscanthus, switchgrass, etc.), which experience chronic removals of all above-ground biomass, the SRC willow plantations in this study cycled more than seven tonnes of leaf litter biomass during the initial four-year rotation. This accumulated leaf litter will play an important role not only in augmenting SOC levels, but also in long-term nutrient cycling, especially in a sandy soil (e.g., Prince Albert). Less than half of the nutrients immobilized within leaf litter were released during the rotation, with the remainder available for willow uptake during the second rotation. Knowledge of leaf litter nutrient release characteristics is useful for selecting appropriate varieties (e.g., Sherburne) for use in environmentally sensitive areas where enhanced nutrient immobilization within leaf litter would be advantageous for minimizing the risk of contaminating adjacent water bodies. Conversely, selecting varieties (e.g., Fish Creek) with quicker leaf litter nutrient release characteristics for use in SRC willow production would help to satisfy a larger portion of nutritional demand naturally and more economically. Principal component analysis identified numerous key relationships between the measured soil, plant tissue, climate and microclimate variables and observed willow leaf litter decomposition and nutrient release characteristics, namely: i) $LV_{Biomass}$ was influenced more by soil nutrient availability than litter quality; ii) $LV_{Biomass}$ was indirectly related to $k_{Biomass}$; iii) $k_{Nutrient}$ was primarily controlled by litter quality, with relatively little influence of soil nutrient availability; iv) $k_{Nutrient}$ is directly related to $LV_{Nutrient}$ v) LV_N , LV_P , and LV_S are chiefly controlled by soil nutrient availability, while LV_K and LV_{Mg} were mainly dependant on litter quality; vi) SLA and soil C:N strongly influenced $k_{Biomass}$; vii) first-year precipitation (total and growing season rainfall and snowfall) played a prominent role in controlling willow leaf litter decomposition and nutrient release dynamics in semi-arid Saskatchewan; and, viii) surface soil (0-10 cm) temperature is a reliable variable for modelling willow leaf litter dynamics within temperate climates like Saskatchewan, presumably due to its close association with soil biota abundance and activity. Further research is needed to quantify the relative importance of leaf litter nutrient cycling, within the context of N, P, K, S, Ca, and Mg biogeochemical cycling within SRC willow plantations, to provide insight into the long-term sustainability and productivity of these woody biomass energy production systems grown on a variety of soil types in Saskatchewan over multiple rotations.

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Table 1 Selected site characteristics of different willow variety trial sites in Saskatchewan, Canada [adapted from 26]

Site	UTM Co-ordinates	Prior crop	ACC ^a	MAP ^b (mm)	MGSP ^c (mm)	MAT ^d (°C)	MGST ^e (°C)	FFD ^f (#)
Prince Albert	13U 448501 5912029	fallow	5-6	450	295	1.2	14.2	85
Birch Hills	13U 467122 5872616	canola	1-2	420	277	1.3	14.3	90
Saskatoon	13U 389970 5776342	fallow	2-3	375	312	2.6	14.9	112
Estevan	13U 655043 5438201	fallow	3-4	430	341	3.3	15.4	124

^a Agriculture capability classification (Class 1: no significant limitations; Class 2: moderate limitations; Class 3: moderately severe limitations; Class 4: severe limitations; Class 5: very severe limitations; Class 6: limited capability for arable agriculture)

^b Mean annual precipitation (snow + rainfall) during the rotation

^c Mean growing season precipitation during the rotation; growing season length determined using 5 °C soil baseline

^d Mean annual air temperature during the rotation

^e Mean growing season air temperature during the rotation; growing season length determined using 5 °C soil baseline

^f Frost-free days

Table 2 Selected soil characteristics of different willow variety trial sites in Saskatchewan, Canada^a

Site	Soil type ^b	Texture	BD	pH _{1:2} ^c	EC _{1:2} ^d	Organic C	Organic C:N
		(% sand/clay)	(kg m ⁻³)		(dS m ⁻¹)	(%)	
Prince Albert	OBC	sand to loamy-sand (91/2)	1588	6.6c ^e	0.16c	1.4c	15.5a
Birch Hills	OBC	silt-loam to clay-loam (29/28)	1002	7.0b	0.68a	3.2a	11.4b
Saskatoon	OV	clay (13/70)	1422	7.1b	0.45b	2.3b	9.5c
Estevan	CHR	silt-loam (33/23)	1238	8.0a	0.60ab	2.0b	12.7b

Table 2 (continued)

Site	Extractable nutrients					
	N	P	K	S	Ca	Mg
	(kg ha ⁻¹)					
Prince Albert	55c	148a	715c	92b	14381b	1297d
Birch Hills	68b	16c	1297b	809a	20464a	4336b
Saskatoon	99a	64b	1963a	663a	19905a	9644a
Estevan	99a	36bc	1348b	764a	19404a	3134c

^a 0-60 cm; average values of six 10 cm segments collected using a JMC backsaver probe (Model PN001; Clements Assoc. Inc,

Newton, IA, USA), except for extractable nutrient levels that are summed values of all segments

^b OBC (Orthic Black Chernozem), OV (Orthic Vertisol), and CHR (Cumulic Humic Regosol); taxonomy based on the Canadian System of Soil Classification [63]

^c pH of a 1:2 (soil:water; on a weight basis) extraction

^d Electrical conductivity

^e Means within a column followed by the same letter are not significantly different ($P > 0.05$) using LSD

Table 3 Mean cumulative biomass and nutrient content of leaf litter after an initial four-year rotation for several exotic willow varieties at different plantations in Saskatchewan, Canada

Variety (n=16)	Biomass	N	P	K	S	Ca	Mg
	(Mg ha ⁻¹) ^a	(kg ha ⁻¹) ^b					
Allegany	7.4a ^c	100.8a	12.7a	90.2bc	30.6a	199.5bc	50.4a
Canastota	7.5a	72.8a	19.5a	157.6a	23.2ab	285.6ab	37.6a
Fish Creek	5.6b	80.8a	13.9a	63.8c	16.2b	187.2c	39.5a
Sherburne	7.0a	83.9a	12.0a	85.0bc	23.5a	239.0abc	41.3a
SX61	7.6a	75.7a	13.8a	129.3ab	26.2a	299.9a	37.7a
SX64	7.7a	70.7a	15.5a	122.6ab	27.5a	323.1a	40.8a
Site (n=24)							
Prince Albert	7.7a ^d	74.2b	35.4a	149.3a	22.7ab	280.8b	24.7c
Birch Hills	7.2a	65.9b	10.4b	126.9a	28.8a	237.3b	40.7b
Saskatoon	4.6b	68.9b	6.4c	43.6b	13.5b	107.1c	32.5bc
Estevan	9.1a	114.1a	6.1c	112.5a	33.1a	397.7a	66.9a
Overall Mean (n = 96)	7.4 (0.3) ^e	82.5 (3.7)	15.3 (1.7)	114.8 (8.0)	25.7 (1.5)	264.0 (16.8)	42.5 (2.4)

^a Estimated by collecting all of the leaves from three representative stems within each plot in early September and extrapolating the leaf biomass to a stand level based on stem density measurements. The estimated stand level leaf biomass was corrected for the foliar nutrient mass loss during leaf senescence

^b Estimated by multiplying the nutrient concentrations of abscising leaves collected in November by the total leaf biomass estimates

^c Among the varieties, means within a column followed by the same letter are not significantly different ($P > 0.05$) using LSD

^d Among the sites, means within a column followed by the same letter are not significantly different ($P > 0.05$) using LSD

^e Mean (standard error)

Table 4 Mean leaf litter decomposition rate constant (k_{Biomass} ; year^{-1}), decomposition limit value (LV_{Biomass} ; %), and asymptote (A) of native and exotic willow varieties, measured using leaf litter bag incubations at different plantations in Saskatchewan, Canada. The proportion of leaf litter biomass remaining after three years was fitted to a nonlinear asymptotic decomposition model

	k_{Biomass}	LV_{Biomass}^a	A^b
Variety (n=16)			
Native	1.6 (0.1) ^c	62.8 (2.2)	0.37 (0.02)
Allegany	1.7 (0.1)	80.1 (1.8)	0.20 (0.02)
Canastota	1.5 (0.1)	80.8 (1.5)	0.19 (0.02)
Fish Creek	1.9 (0.1)	82.8 (1.6)	0.17 (0.02)
Sherburne	1.8 (0.3)	84.7 (1.5)	0.15 (0.02)
SX61	1.8 (0.1)	78.6 (2.1)	0.21 (0.02)
SX64	1.5 (0.1)	82.0 (1.3)	0.18 (0.01)
Site (n=28)			
Prince Albert	2.0 (0.1)	72.7 (1.4)	0.27 (0.01)
Birch Hills	1.4 (0.1)	81.8 (1.7)	0.18 (0.02)
Saskatoon	1.6 (0.1)	79.5 (2.4)	0.21 (0.02)
Estevan	1.7 (0.1)	81.4 (1.1)	0.19 (0.01)

^a $(1 - A) \times 100$

^b The recalcitrant proportion of initial leaf litter mass with a practical decomposition rate of zero

^c Varietal and site mean (standard error) values are reported due to significant ($P < 0.05$) variety \times site effect

Table 5 Mean leaf litter nutrient release rate constant (k_{Nutrient} ; year^{-1}) of native and exotic willow varieties, measured using leaf litter bag incubations at different plantations in Saskatchewan, Canada. The proportion of initial leaf litter nutrient content remaining after three years was fitted to a single exponential model

	N	P	K	S	Ca	Mg
Variety (n=16)						
Native	0.39b ^a	0.64bc	1.29ab	1.1ab	1.2ab	1.00c
Allegany	0.44b	0.70b	0.94c	0.7d	1.0bc	1.07bc
Canastota	0.43b	0.66b	1.41a	1.0bc	0.9cd	0.94c
Fish Creek	0.64a	0.98a	1.39a	1.4a	1.5a	1.54a
Sherburne	0.41b	0.47d	0.76d	0.4e	0.4e	0.66d
SX61	0.45b	0.55cd	0.98c	1.0bc	1.2ab	1.23ab
SX64	0.41b	0.50d	1.11b	0.8cd	0.8d	1.07bc
Site (n=28)						
Prince Albert	0.33c ^b	0.52c	1.64a	0.76b	0.85b	1.29a
Birch Hills	0.43b	0.71b	1.14b	0.86b	1.01ab	1.16a
Saskatoon	0.45b	0.70b	0.78d	0.83b	1.08ab	0.97b
Estevan	0.61a	0.87a	0.95c	1.21a	1.10a	0.87b

^a Among the varieties, means within a column followed by the same letter are not significantly different ($P > 0.05$) using LSD

^b Among the sites, means within a column followed by the same letter are not significantly different ($P > 0.05$) using LSD

Table 6 Mean nutrient release limit value (LV_{Nutrient} ; %) of initial nutrients contained within the leaf litter of native and exotic willow varieties after three years, measured using leaf litter bag incubations at different plantations in Saskatchewan, Canada

	N	P	K	S	Ca	Mg
Variety (n=16)						
Native	61.5c ^a	82.5b	75.2c	63.6d	55.6b	74.8c
Allegany	78.2ab	83.2b	82.0b	80.3c	85.9a	90.2ab
Canastota	75.5bc	82.5b	90.4a	84.2abc	87.0a	89.3ab
Fish Creek	86.0a	89.1a	90.0a	89.6a	92.6a	94.9a
Sherburne	76.1ab	81.0b	86.4ab	85.1abc	91.0a	92.5ab
SX61	70.5bc	75.7c	87.9ab	82.1bc	81.9a	89.6ab
SX64	76.7ab	84.9ab	90.6a	87.1ab	91.1a	89.3b
Site (n=28)						
Prince Albert	59.2b ^b	72.1c	90.6a	74.0b	77.0a	91.0a
Birch Hills	82.1a	89.5a	93.3a	82.8a	86.3a	93.7a
Saskatoon	80.5a	84.1b	75.7c	85.9a	86.4a	83.5b
Estevan	77.7a	84.9b	84.5b	83.8a	84.4a	86.2b

^a Among the varieties, means within a column followed by the same letter are not significantly different ($P > 0.05$) using LSD

^b Among the sites, means within a column followed by the same letter are not significantly different ($P > 0.05$) using LSD

Table 7 Mean nutrients released (kg ha⁻¹) from leaf litter decomposition during an initial four-year rotation for six exotic willow varieties, measured using leaf litter bag incubations at different plantations in Saskatchewan, Canada^a.

	N	P	K	S	Ca	Mg
Variety (n=16)						
Allegany	25.9 (5.6) ^b	3.4 (0.4)	29.6 (5.6)	11.2 (2.2)	81.1 (14.6)	21.4 (3.4)
Canastota	17.0 (2.1)	5.9 (1.8)	72.6 (15.3)	10.1 (1.5)	112.1 (22.1)	15.1 (1.7)
Fish Creek	24.6 (4.3)	3.7 (0.8)	24.2 (5.2)	7.6 (1.2)	91.5 (18.7)	21.9 (3.6)
Sherburne	23.0 (3.2)	3.2 (0.6)	35.0 (7.7)	9.9 (1.4)	97.6 (14.4)	19.3 (1.6)
SX61	21.8 (3.3)	3.1 (0.7)	69.6 (21.5)	12.8 (2.5)	142.0 (36.4)	18.6 (2.6)
SX64	15.6 (1.9)	4.1 (0.9)	53.9 (10.2)	11.2 (1.5)	139.1 (25.2)	15.0 (1.7)
Site (n=24)						
Prince Albert	18.5 (2.0)	8.4 (1.1)	100.7 (13.2)	11.9 (1.4)	158.1 (20.3)	16.1 (1.9)
Birch Hills	16.8 (1.4)	3.0 (0.2)	32.1 (3.7)	11.8 (1.3)	79.1 (6.1)	21.2 (1.9)
Saskatoon	13.1 (1.2)	1.6 (0.1)	10.8 (0.9)	3.6 (0.3)	25.3 (1.9)	11.3 (1.0)
Estevan	37.4 (3.7)	2.5 (0.2)	45.4 (4.0)	14.6 (1.0)	185.6 (14.5)	25.3 (2.2)

^a The decomposing leaf litter cohorts considered were three years of pre-coppice leaf litter, two years of first year post-coppice leaf litter, and one year of nutrient release from second year post-coppice leaf litter.

^b For each nutrient, varietal and site mean (standard error) values are reported due to significant ($P < 0.05$) variety \times site effect

Fig. 1 Locations of four short-rotation coppice willow variety trial study sites in Saskatchewan, Canada. ArcGIS10 (Environmental Systems Research Institute, Inc, Redlands, CA, USA) map courtesy of Dr. Beyhan Amichev

Fig. 2 Mean ($n = 4$) percent of initial leaf litter mass remaining of native and exotic willow varieties, measured using a three-year leaf litter bag incubation at different plantations in Saskatchewan, Canada. For each year, means with the same letter are not significantly different ($P > 0.05$) using LSD

Fig. 3 Percentage of initial leaf litter nutrients remaining of native and exotic willow varieties, measured using a three-year leaf litter bag incubation at different plantations in Saskatchewan, Canada. For each year, means with the same letter are not significantly different ($P > 0.05$) using LSD. Note: $n = 16, 28$, and 112 for comparisons among varieties, cites, and nutrients, respectively.

Fig. 4 Principal component analysis of plant tissue and soil properties associated with leaf litter decomposition and nutrient release variables of several native and exotic willow varieties, measured using leaf litter bag incubations at different plantations in Saskatchewan, Canada. Variables analyzed were: leaf litter decomposition rate constant (k_{Biomass}) and limit value (LV_{Biomass}); leaf litter nutrient release rate constant (k_{Nutrient}) and limit value (LV_{Nutrient}) for N, P, K, S, Ca, and Mg; specific leaf area (SLA); leaf litter nutrient concentration ($[]$) for N, P, K, S, Ca; and soil (Soil) pH, organic C:N, along with initial extractable levels of $\text{NH}_4^+\text{-N} + \text{NO}_3^-\text{-N}$, P, K, S, Ca, and Mg

Fig. 5 Principal component analysis of meteorological properties and canopy variables associated with leaf litter decomposition and nutrient release variables of several native and exotic willow varieties, measured using leaf litter bag incubations at different plantations in Saskatchewan, Canada. Variables analyzed were: leaf litter decomposition rate constant (k_{Biomass}) and limit value (LV_{Biomass}); leaf litter nutrient release rate constant (k_{Nutrient}) and limit value (LV_{Nutrient}) for N, P, K, S, Ca, and Mg. Also included were the yearly (YR_1 , YR_2 , and YR_3): annual (AP) and growing season (GSP) precipitation; relative humidity (RH); potential evapotranspiration (PET); aridity index (AI); mean daily air temperature (AT), wind speed (WS), soil temperature (ST; 0-10 cm); growing season length based on either mean daily air temperatures (GSL(A)) or 0-60 cm soil temperatures (GSL(S)); average stem height (SH); stem basal area (SBA); leaf surface area (LSA)

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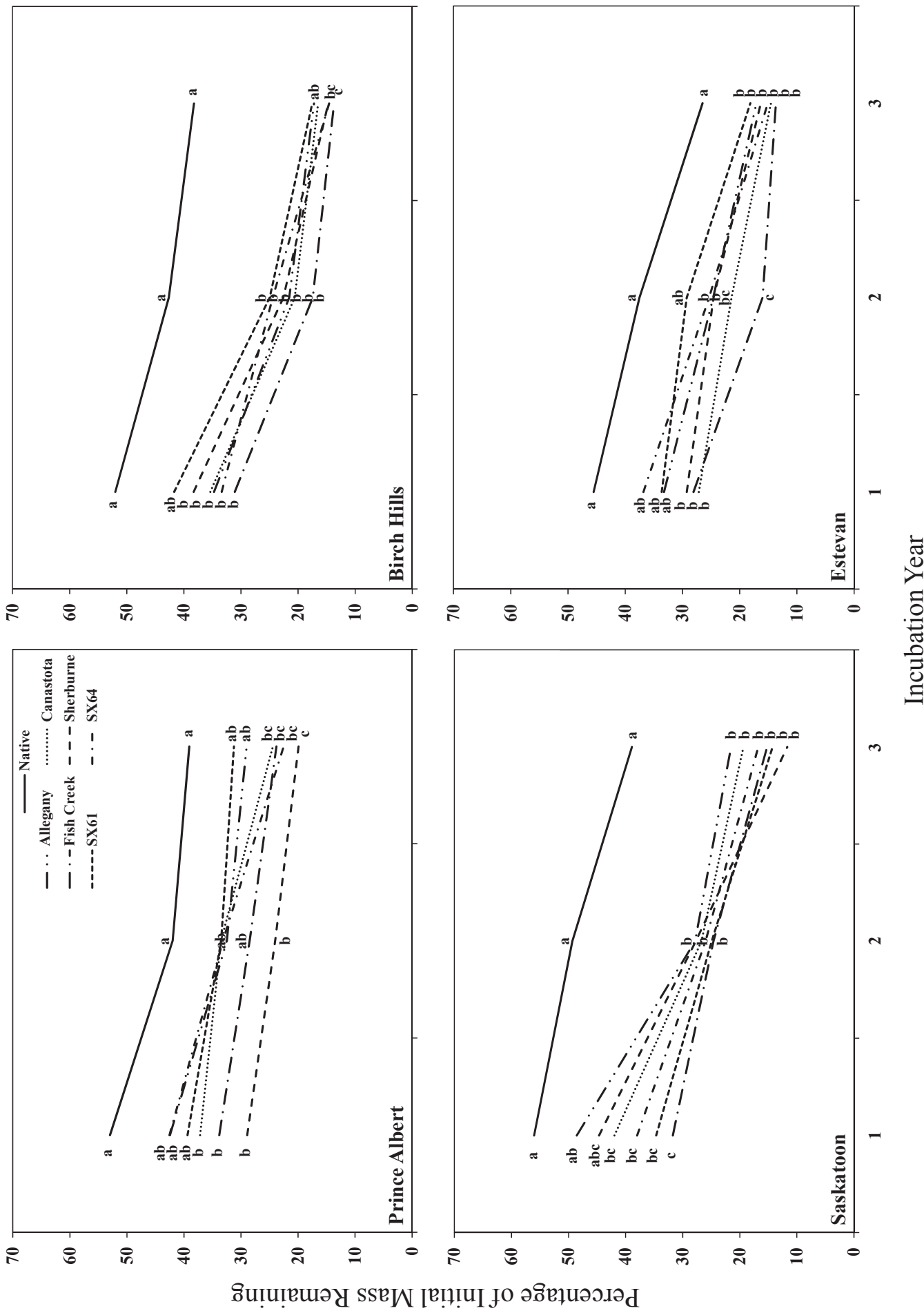


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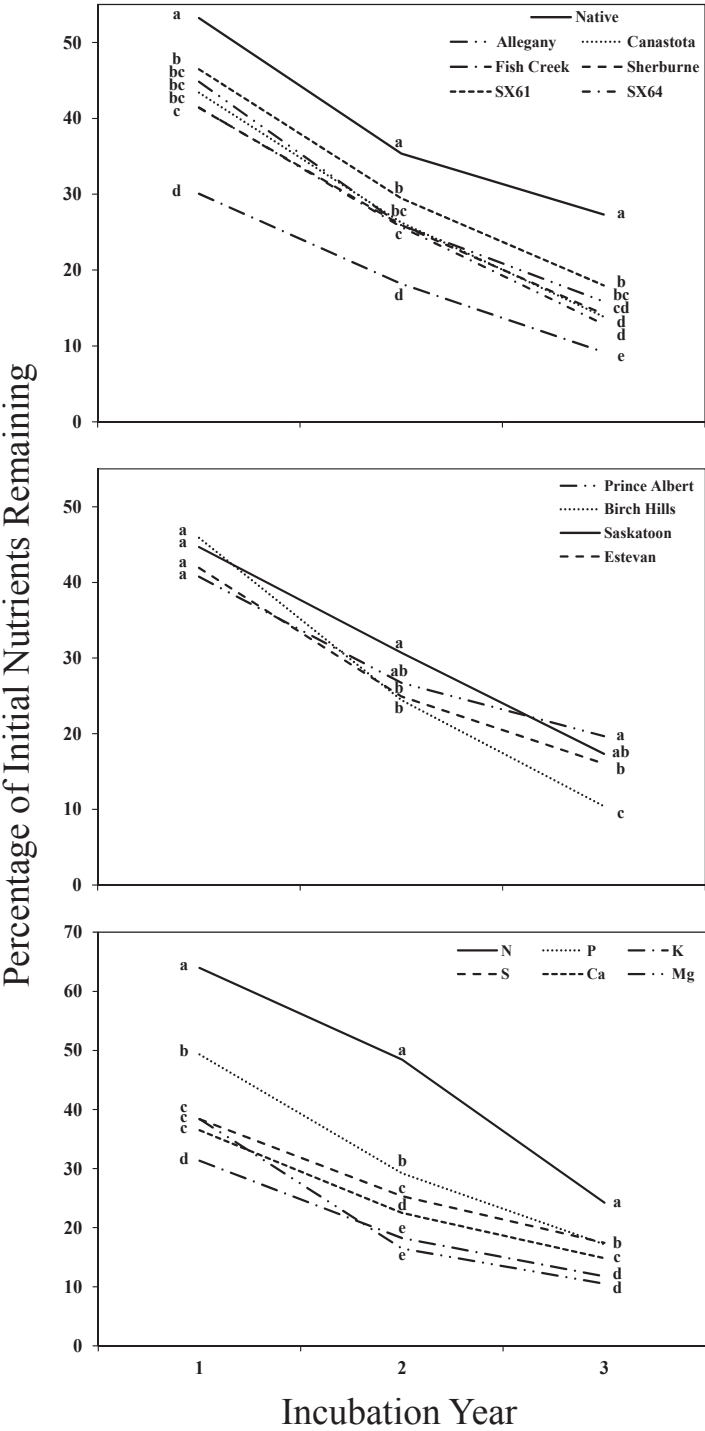


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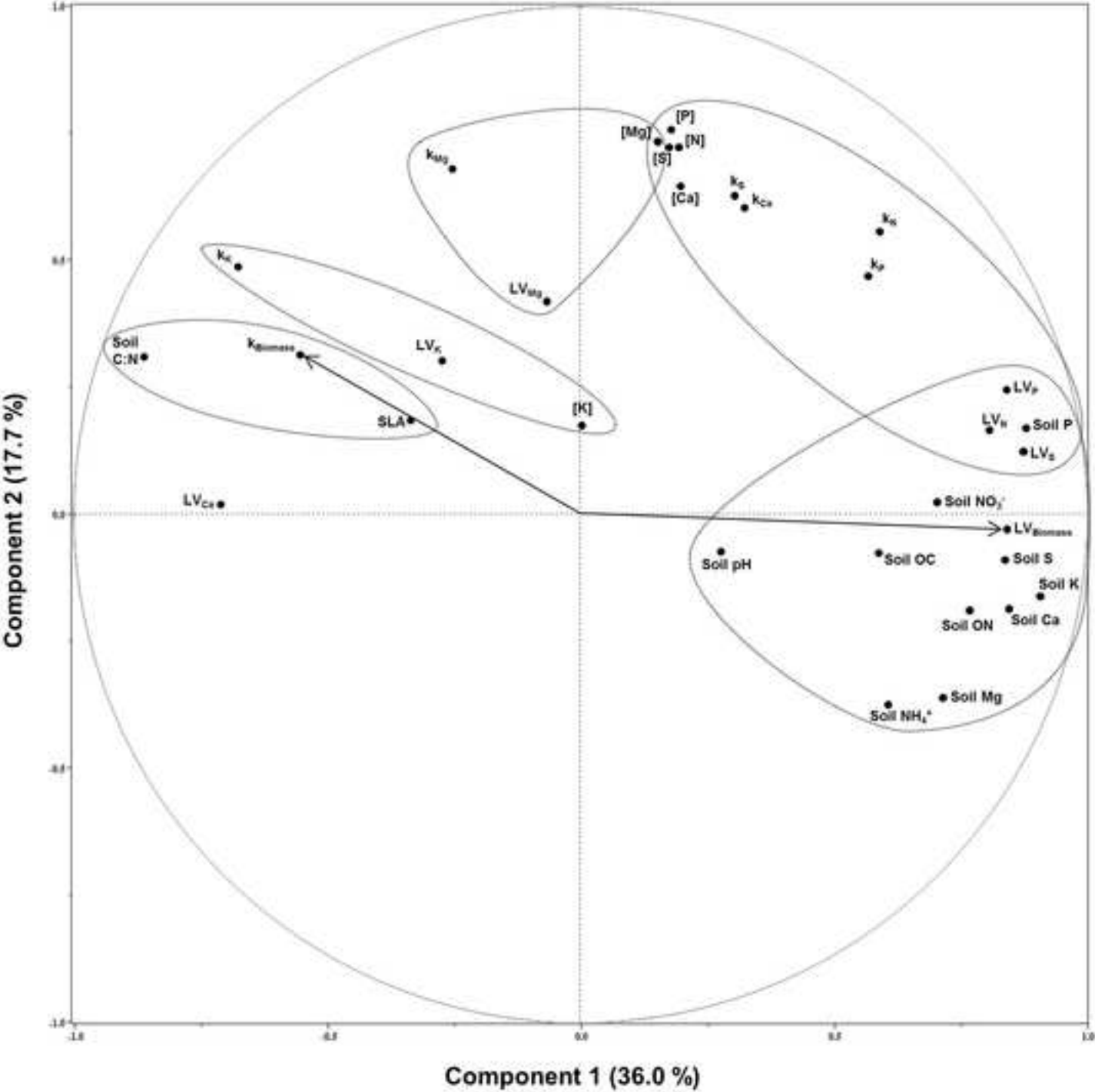


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