

Can short-term litter-bag measurements predict long-term decomposition in northern forests?

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Abstract

Background and aims The litter-bag technique has become common in the estimation of the rates of decomposition, but in many cases the bags are incubated for only a short period, raising the issue of the extent to which short-term incubations represent long-term litter decomposition. We addressed this using 12 years of data from the CIDET study.

Methods The CIDET study involved placement of 10 foliar litters on the soil surface and wood blocks on the soil surface and buried across temperate to subarctic Canada. Bags were retrieved 10 times over 12 years at 19 sites and the residual litter mass determined.

Results A literature search revealed that 84% of published litter-bag studies in temperate-boreal-subarctic regions were of 3 years duration or less. The strength

of the relationship between the mass loss after 1 year and later years at each CIDET site, expressed as the coefficient of determination (R^2) among the 12 litters, decreased with length of incubation, reaching an average of only 0.4 after 12 years. The R^2 value was inversely related to mean annual temperature. The single exponential model of mass remaining (k) declined with length of incubation, and the rate of decline varied among litter types and sites. For 3 litters at 19 sites, the 3- and 12-year k values were strongly related.

Conclusions These results show that caution should be exercised when extrapolating short-term litter-bag studies (e.g. < 3 years), particularly in temperate climates.

Keywords Litter-bags · Decomposition · Forest soils · Litter · Canadian Intersite decomposition experiment

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Introduction

The litter-bag method, in which the mass of litter incubated in mesh bags is measured over time, has become the standard method for estimating rates of litter decomposition, and thousands of litter-bag studies have been conducted (Prescott 2005; Harmon et al. 2009). Most of these studies have been of short duration. A survey of length of exposure of litter-bag studies in temperate, boreal and subarctic ecosystems revealed that most (69%) were of 1 to 2 years in duration, 84% were 3 or fewer years in duration, and only 5% were exposed for more than 5 years (Fig. 1).

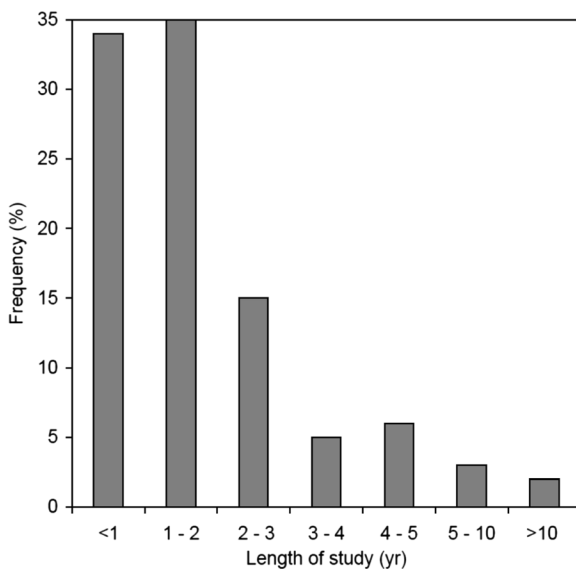


Fig. 1 The exposure period of litter-bag studies in temperate, boreal and subarctic regions based on a literature search ($n = 171$) on ISI Web of Science, using LITTER, DECOMPOS* OR DECAY, BOREAL OR TEMPERATE OR SUBARCTIC and NOT STREAM

Short-term studies are useful for characterizing early stages of the decomposition process, and we are now able to predict with confidence short-term rates of decomposition of litters in most ecosystems (Prescott 2010). However, short-term litter-bag studies are of questionable use for predicting and modeling rates of decomposition during the late stages of decay, the ‘maximum decomposition limit’ or asymptote (Berg and Ekbohm 1991; Harmon et al. 2009), or predicting the proportion of the litter which enters the slowly decomposing humus pool (Cotrufo et al. 2015). Such knowledge is essential for accurate modeling of carbon stores and fluxes from forest soils. Short-term studies are a lesser problem in regions, such as the moist Tropics, where decomposition is fast (Cusack et al. 2009), but in cold, northern forests, litter can take decades to decompose, and tends to be transformed into humus, which decays exceedingly slowly (Berg and Ekbohm 1991).

Long-term patterns of decomposition have been predicted from short-term mass loss data by applying models to the early mass-loss data. Single or dual exponential models usually fit early-stage mass-loss data, and the rate constant or ‘ k value’ (Olson 1963) is commonly used to characterize and compare decomposition rates among litters and ecosystems. These models have also been used to predict long-term patterns of decomposition; for example, Hobbie et al. (2000) used 1-year mass

loss rates as a surrogate for the contribution of different litter types to soil organic matter in northern soils. Some of the few long-term litter decomposition studies to date have demonstrated that patterns of early decomposition among varying litters at one site are not necessarily indicative of the long-term decomposition rate, which may influence the amount of litter that enters the soil organic matter pool (e.g. Berg and Ekbohm 1991; Prescott et al. 2000). In a 23-year litter-bag experiment in an English peat bog (Latter et al. 1998), the rankings of *Calluna* shoots, *Calluna* stems and *Eriophorum* leaves by % mass loss or decay rate (k) after 1 year (stems < shoots < leaves; 8%, 16%, 27%; 0.083, 0.174, and 0.314; respectively) were not strongly correlated with that after 23 years (stems < leaves < shoots; 63%, 65%, 70%; 0.043, 0.046, 0.052; respectively). The relative variation in mass loss among replicate litter bags increased with time, as also noted by Bradford et al. (2016).

Harmon et al. (2009) used data from the Long-term Intersite Decomposition Experiment Team (LIDET) experiment to examine how well short-term decomposition rates predicted long-term carbon storage. In the LIDET experiment, nine litter types were placed at 27 sites throughout the U.S.A. and retrieved over a period of 10 years. They reported that the single negative exponential model predicted over 85% of the mass loss in about half the 234 cases (litter \times site combinations) and its natural logarithm transformation had $P < 0.05$ in 87% of the cases. However, dual exponential and asymptotic models fit in more cases than the single exponential model, and the long-term integrated decomposition rate was on average 75% of that of the first year of decomposition, indicative of a common, but not universal, slow phase of decomposition in the late stage. They concluded that using short-term decomposition rates to model carbon stores would underestimate the litter stores by at least one-third. This problem may be even more pronounced in northern forests, in which a late-stage, slow phase is common, and which represented only 3 of the 27 sites in the LIDET study.

The objective of this paper is to assess how well in general, and under which circumstances, short-term litter mass-remaining data accurately predict long-term values in northern forests. We employ the dataset of the Canadian Intersite Decomposition Experiment (CIDET) study. In CIDET, mass remaining was measured of 10 foliar litters plus surface and buried wood blocks at 21 forest and wetland sites in Canada over 12 years. We first assess how well relative

Table 1 The 10 litter types plus wood blocks (A) and 19 sites (B) used in this study (from Trofymow and CIDET Working Group 1998)

A			
Litter type			
Trembling aspen leaves (<i>Populus tremuloides</i>)			
American beech leaves (<i>Fagus grandifolia</i>)			
White birch leaves (<i>Betula papyrifera</i>)			
Western redcedar needles (<i>Thuja plicata</i>)			
Douglas-fir needles (<i>Pseudo-tsuga menziesii</i>)			
Fescue grass (<i>Festuca halii</i>)			
Bracken fern (<i>Pteridium aquilinum</i>)			
Jack pine needles (<i>Pinus banksiana</i>)			
Black spruce needles (<i>Picea mariana</i>)			
Tamarack needles (<i>Larix laricina</i>)			
Western hemlock wood blocks (<i>Tsuga heterophylla</i>): buried and placed on the soil surface			
B			
Site, province and notation	Ecoclimatic province	Major tree species	Mean annual temperature 1992–2004 (°C)
Batoche, SK (BAT)	Transitional grassland	No trees: shrubs, sedges and mosses	2.0
Rocky Harbour, NF (CBR)	Maritime low boreal	<i>Abies balsamea</i>	4.5
Chapleau, ON (CHA)	Humid low boreal	<i>Pinus banksiana</i>	1.9
Gander, NF (GAN)	Maritime mid-boreal	<i>Abies balsamea</i>	4.2
Gillam upland, MB (GI1)	Low subarctic	<i>Picea mariana</i>	−3.8
Gillam peatland, MB (GI2)	Low subarctic	No trees: shrubs and mosses	−3.8
Hidden Lake, BC (HID)	Moist montane southern cordilleran	<i>Thuja heterophylla/Thuja plicata</i>	6.6
Inuvik, NWT (INU)	High subarctic	<i>Picea mariana</i>	−7.6
Kananaskis, AB, (KAN)	Montane south cordilleran	<i>Pinus contorta</i>	3.6
Morgan Arboretum, QC (MAR)	Humid mid-cool temperate	<i>Fagus grandifolia</i>	6.7
Montmorency, QC (MON)	Perhumid low boreal	<i>Abies balsamea</i>	0.9
Nelson House upland, MB (NH1)	Subhumid high boreal	<i>Pinus banksiana</i>	−2.9
Nelson House peatland, MB (NH2)	Subhumid high boreal	No trees: shrubs, sedges and mosses	−2.9
Port McNeill, BC, (PML)	Maritime south pacific cordilleran	<i>Thuja heterophylla</i>	8.7
Schefferville, PQ (SCH)	Low subarctic	<i>Picea mariana</i>	−4.2
Shawnigan Lake, BC (SHL)	Coastal south pacific cordilleran	<i>Pseudotsuga menziesii</i>	9.3
Termundee, SK (TER)	Transitional grassland	<i>Populus tremuloides</i>	3.7
Topley, BC (TOP)	Boreal southern cordilleran	<i>Pinus contorta/Picea glauca</i>	1.5
Whitehorse, YK (WHI)	Boreal northern cordilleran	<i>Pinus contorta</i>	0.0

decomposition rates among the litters at sites are preserved by comparing the coefficient of determination of mass remaining from years 1 through 12. If short-term mass loss is a good predictor of long-term mass loss, we expect to find a strong positive relationship between the yearly values. We then calculate the exponential decay coefficient (k) of three litters, *Picea mariana* needles, *Betula papyrifera* leaves and *Festuca halii* shoots, from 1 through to 12 years at each site. We determine how the k

values change with time, and test how well short-term k values predict those over the long-term.

Methods

Details of the CIDET experiment are provided in Trofymow and CIDET Working Group (1998). In brief, 10 foliar litters and a wood block were placed in

20 × 20 cm polypropylene litter-bags (openings 0.25 × 0.50 mm) on the forest floor, with a second set of wood blocks buried beneath the surface (Table 1). There were 21 sites representing the major forest ecoclimatic zones across Canada (see Fig. 1 in Trofymow et al. 2002). The Prince Albert (PAL) and Petawawa (PET) sites were excluded from the analyses because fire destroyed the litter-bags after 8 and 6 years, respectively. Quadruplicate litter-bags were collected after 1, 2, 3, 4, 5, 6, 7, 8, 10 and 12 years, the residual litter removed, cleaned, oven dried and weighed and expressed as the mass remaining of the original litter, as the mean of the quadruplicate bags.

To assess the strength of the relationship between mass remaining collected at 1 through 10 years and that collected at 12 years for the 12 litter types retrieved (10 foliar and wood blocks placed on the soil surface and buried), we calculated the coefficient of determination (R^2) for each retrieval date at each of the 19 sites.

We fit the exponential decay model to the mass remaining data, using linear regression of natural-logarithm-transformed mass against time, to calculate the k value as the slope (Olson 1963). This model was fit to data for *Picea mariana* needles, *Betula papyrifera* leaves and *Fescue halii* shoots, representing evergreen needle, deciduous leaf and grass litters, for years 1 ($n = 2$, i.e. years 0, 1) to 12 ($n = 11$, i.e. years 0, 1, 2, 3, 4, 5, 6, 7, 8, 10, 12). It was applied to the 19 sites and we then examined the change in k values for each litter over the 12 years and the change standardized to the k value of each litter and site after 12 years.

Results

Based on data for the 12 litters at each site, there is variation in the strength of the coefficient of determination (R^2) between the mass remaining after 12 years and after 1 year, as illustrated for 4 sites in Fig. 2a. At some sites, such as Gillam 1 [G11], the relationship between mass remaining after 1 and 12 years is strongly positive, at others it is weak but positive (e.g. Port McNeill [PML] and Rocky Harbour [CBR]) and in some cases there is even a negative relationship, although not significant (Morgan Arboretum [MAR]). A similar analysis for each litter type across the 19 sites revealed that the R^2 value for the 10 foliar litters ranged from 0.26 to 0.72 (average 0.40, all $p < 0.05$) and an average slope of 1.39. The pattern for birch, spruce and *Fescue* litters is

illustrated in Fig. 2b. There were non-significant ($p > 0.36$) relationships for the surface and buried wood blocks (R^2 0.05 and 0.00, respectively).

Comparison of the year 1 mass remaining data with subsequent years, through the R^2 derived from the 12 litters at each site, showed a progressive overall decrease, starting at an average of 0.90 when comparing 1- and 2-year mass remaining, but falling to an average of 0.41 when comparing 1- and 12-year mass remaining (Fig. 3a). There is substantial variation in the coefficient of determination among the sites, for each temporal comparison. Similarly, when comparing the 12-year mass remaining with that for the preceding years, the average R^2 value falls with increasing time, with average R^2 values of 0.41, 0.46 and 0.52 for mass remaining after 1, 2 and 3 yr. and the average R^2 for 10-year mass remaining is only 0.60 (Fig. 3b).

We compared the variation in average R^2 of the 1 to 12-year mass remaining among the 19 sites (as derived for each site in Fig. 3a) with the mean annual temperature and the average 12-year mass remaining. There was a significant negative relationship between the average R^2 and the 1992–2004 mean annual temperature at the site, which is a strong control on the overall rate of decomposition across these sites (Trofymow et al. 2002; Fig. 4a). There was a strong positive relationship between the average R^2 and the litter mass remaining after 12 years, as the average of the 12 litters (Fig. 4b). These show that the 1-year mass remaining may be a reasonable predictor of 12-year decomposition rates in soils which are cold and decomposition is slow (generally >50% of original mass remaining after 12 yr), but the predictive capacity is weak in soils that are warmer and decomposition is faster (generally <25% of original mass remaining after 12 years). The strong correlation in cold soils may just be because they have not progressed as far, even after 12 years, along the decomposition pathway to soil organic matter.

We examined the change in k value through years 1 to 12 (years 9 and 11 were not sampled) for the three litters at the 19 sites (Fig. 5a to c), and expressed as a percentage of the final (12-year) k value, to standardize across sites (Fig. 5d to f). There is a clear decrease in the k value with time at nearly all sites/litters. The pattern is particularly pronounced with the *Fescue* litter, because it contains a large amount of easily decomposed material, which is rapidly lost in the first and second years, except at two sites (Inuvik [INU] and Nelson House peatland [NH2]). The pattern is less pronounced with the birch

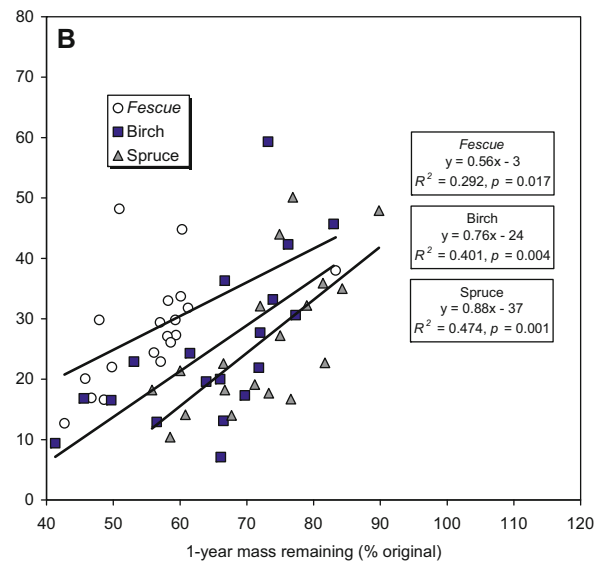
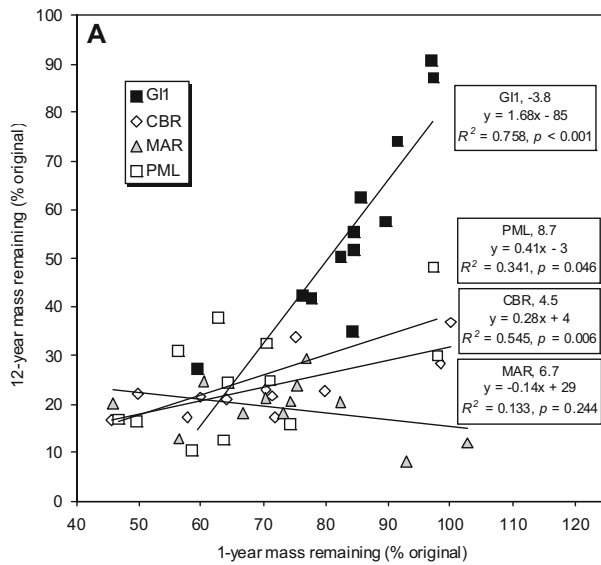


Fig. 2 Relationship between mass remaining (as percentage of original) after 1 and 12 years of (a) twelve litters at four sites covering a range of mean annual temperatures (°C) Gilliam 1 (GI1,

–3.8), Port McNeill (PML, 8.7), Rocky Harbour (CBR, 4.5) and Morgan Arboretum (MAR, 6.7); (b) three litters (representing coniferous needles, deciduous leaves and graminoid) at 19 sites

leaves and spruce needles. The k value based on 3 years of decomposition is on average 189% and 152% of the k value for 12 years of decomposition for the spruce needles and birch leaves, respectively, and 311% for the *Fescue*. The exponential rate of decline in the k value over the 10 collections averaged 0.095, 0.071 and 0.148 yr⁻¹ for the birch, spruce and *Fescue* litters, respectively, and the differences among the sites were

not strongly ($p = 0.06$ (*Fescue*), 0.12 (birch) and 0.42 (spruce), data not shown) correlated with the site mean annual temperature.

Can short-term k values predict long-term? For these three litters across 19 sites, the 3-year k value was significantly correlated ($p < 0.05$) with that derived from the 12-year data, with R^2 values of 0.47, 0.43 and 0.25 for birch, spruce and *Fescue*, respectively (Fig. 6). The

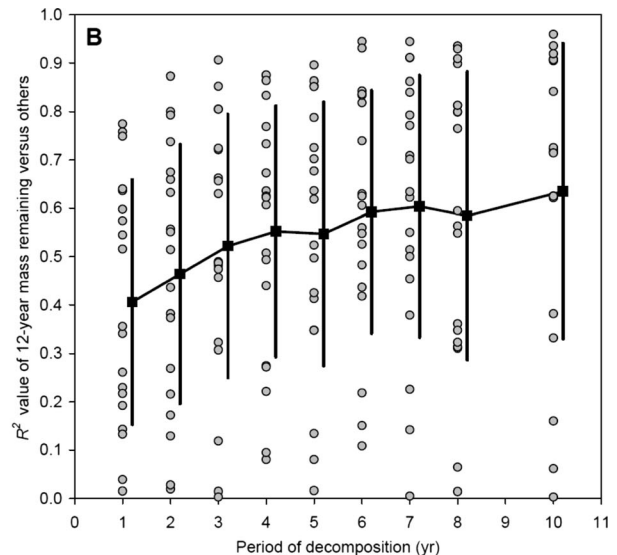
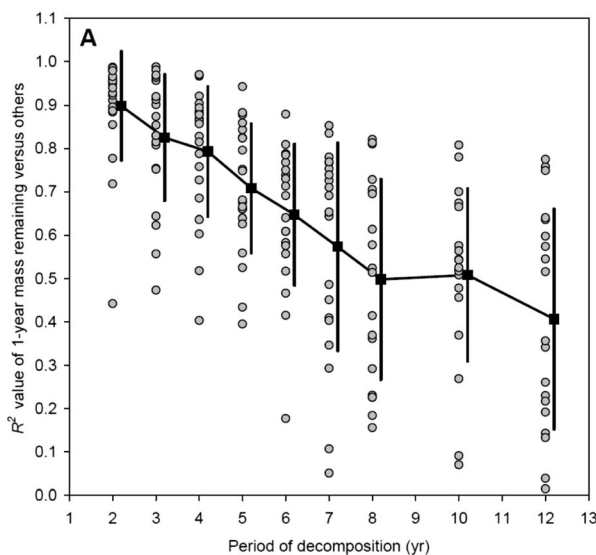


Fig. 3 The coefficient of determination (R^2) between the mass remaining at the CIDET sites (a) after 1 year and that after 2, 3, 4, 5, 6, 7, 8, 10 and 12 years and (b) after 12 years and that after 1, 2,

3, 4, 5, 6, 7, 8 and 10 years. Circles represent individual sites and the squares represent the mean for each year; the vertical line is the standard deviation of the mean

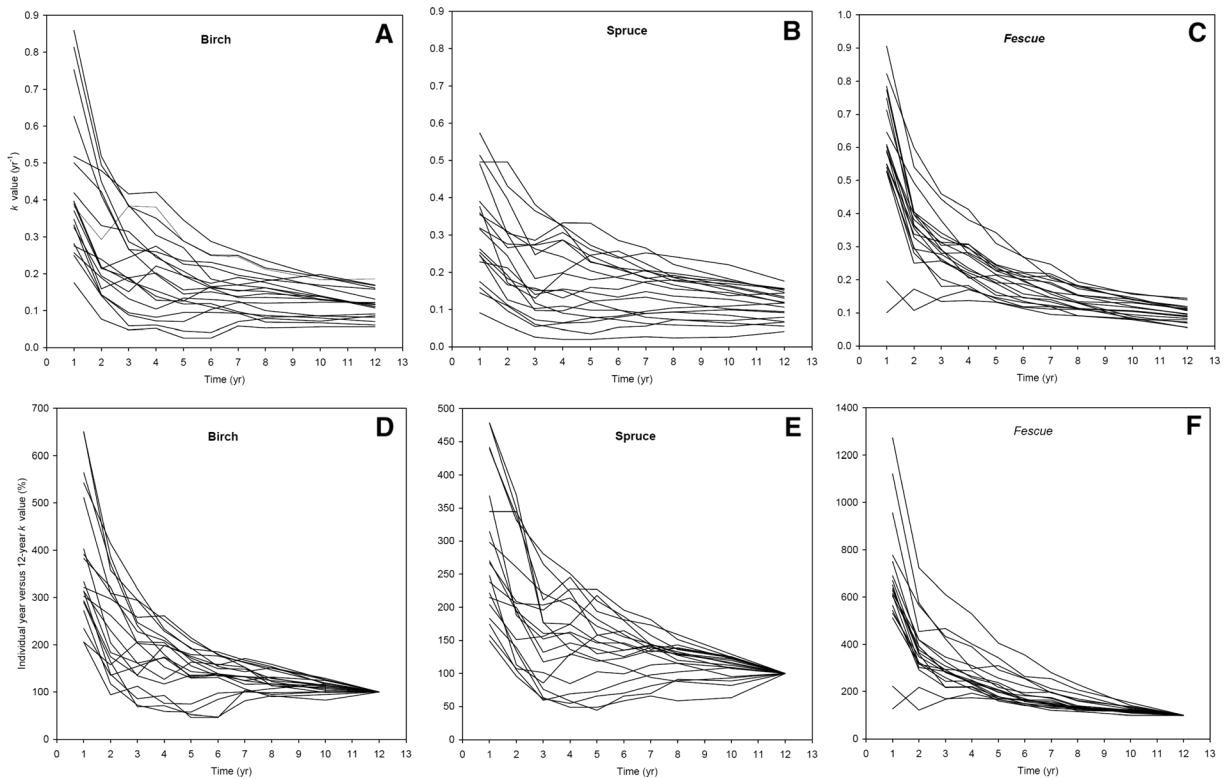


Fig. 5 Changes in exponential decay k value of decomposing birch leaves (a), spruce needles (b) and *Fescue* shoots (c) at the 19 sites, and then standardized k values for each year presented as a percentage of the k value at 12 years (d, e and f, respectively).

These values were calculated using mass remaining from year 1 (fit to data for years 0 and 1) to year 12 (fit to data from years 0, 1, 2, 3, 4, 5, 6, 7, 8, 10 and 12)

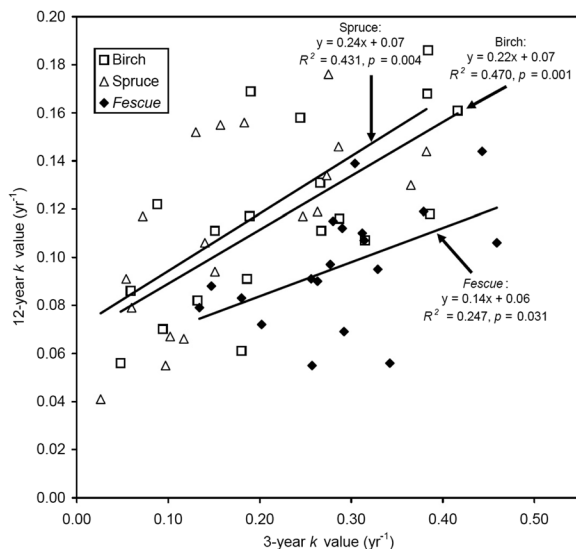


Fig. 6 Relationship between the exponential k value determined after 3 years with that after 12 years, for birch, spruce and *Fescue* litters at the 19 sites

(Currie et al. 1999; Adair et al. 2008; Zhang et al. 2008), FLDM, DOCMOD, CANDY and SOMM (Zhang et al. 2008), YASSO (Tuomi et al. 2009), CBM-CFS3 (Smyth et al. 2010), and the N mineralization model of Manzoni et al. (2008).

As noted by Prescott (2005), litter-bag studies purport to determine the rates at which litter decomposes in the early stages and perhaps identify the ‘maximum decomposition limit’ – the point at which litter becomes humus. Our study shows, however, that while the mass remaining after 1, 2 or 3 years may be a good predictor of the mass remaining after 12 years in those systems in which decomposition is slow (for example, those in which the average mass remaining after 12 years is >50%). For those systems in which decomposition is advanced after 12 years (average mass remaining after 12 years is <25%), the predictive ability is poor.

Using LIDET data, Harmon et al. (2009) applied a series of different functions and concluded that the single exponential function was ‘biologically reasonable’ for 27 to 65% of the cases tested and that the

global store of litter estimated using short-term decomposition rates would be underestimated by at least one-third. Our CIDET results for three litters also show that predictions of decomposition with a single exponential equation shows that the k value declines with a lengthening of the period of incubation, but that this varies with site and litter type.

While short-term litter bag studies can be used to identify changes in litter mass and properties where the patterns occur in the early stages of decomposition, our results suggest that caution should be exercised applying such results to later stages and extrapolating from short- to long-term rates.

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