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Mass Loss, Nitrogen, Phosphorus and Potassium Release Patterns and Non-additive Interactions in a Decomposition Study of Chir Pine (*Pinus roxburghii*) and Oak (*Quercus griffithii*)

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ABSTRACT

Soil fertility and crop production in developing countries, to a large extent, are based on traditional methods of using leaf litters, hence understanding the litter nutrient dynamics is important to optimize their use for sustainable crop production. Mass loss, nutrients N, P and K release patterns and additive/non-additive interactions of leaf litters of chir pine (*Pinus roxburghii*) and oak (*Quercus griffithii*) were investigated in a decomposition study using the litterbag technique. Study consisted of five treatments: 100% chir pine, 100% oak, 50% chir pine: 50% oak, 30% chir pine: 70% oak and 70% chir pine: 30% oak with four replications in a randomized complete block design. Significant differences were found in mass loss and nutrient contents among the treatments ($p<0.05$). Non-additive interactions (synergistic-antagonistic) were found in the litter mixtures. Synergistic effects were more common in N, confirming that mixing oak with chir pine enhanced N mineralization. Antagonistic interactions were more pronounced in P while for K, synergistic interactions were observed in litter mixtures with high proportion of oak (70%) and antagonistic interactions were found in mixtures with high proportion of chir pine. It is evident from the study that mixing high proportion of oak with chir pine enhances mass loss and nutrient mineralization. Non-additive interactions indicate the possibility of synchronising nutrient release and plant nutrient demand through litter manipulation by mixing high with low litter quality. It is concluded that litter mixture in proportion of 70% oak and 30% chir pine is the optimal litter mixture for enhancing decomposition and nutrient release.

Key words: Chir pine, oak, mass loss, non-additive, synergistic-antagonistic

INTRODUCTION

Leaf litters of different tree species are commonly used as organic fertilizers in agricultural systems in the Himalayan regions. Some of the major leaf litter trees used by the farming communities in Bhutan are *Quercus griffithii*, *Q. lanata*, *Q. semecarpifolia*, *Pinus roxburghii*, *Pinus wallichiana*, *Schima wallichii*, *Castanopsis indica* and *Alnus nepalensis* (Roder *et al*., 2003). Similarly, Misra *et al*. (2008) also reported the use of *Quercus* spp., *Acer oblongum*, *Aesculus indica*, *A. nepalensis* and *Juglans regia* by farmers in middle hills in Garhwal in

Uttar Pradesh, India. Studies on decomposition and nutrient release patterns of these leaf litters are scarce in the mentioned regions. Litter decomposition is crucial in converting the organic forms of nutrients to plant available forms (Hirobe *et al*., 2004). Decomposition is characterised by mass loss. However, nutrient immobilization/release and the changes in the chemical composition of decaying litters are not always linearly associated with mass loss (Berg and McClaugherty, 2003).

During immobilization processes, decomposers utilize and accumulate nutrients from the soil solution/surroundings and if there is net immobilization, the nutrient content of the decaying material could exceed 100% of the original nutrient content in the organic material (Palm and Sanchez, 1990). Various factors are responsible for decomposition of the organic materials. The important factors controlling organic matter decomposition and nutrient releases are climate, litter quality, decomposer community and their interactions (Gartner and Cardon, 2004). Litter quality is important in determining the rate of litter decay and nutrient release (Bloomfield *et al*., 1993). C:N ratio is one of the most widely used litter quality parameters in predicting rates of litter decomposition and nutrient release (Heal *et al*., 1997). The high initial N concentration of the litters is responsible for the first stage of decomposition and the slow decomposition in the later stages is due to recalcitrant lignin-N complexes (Berg *et al*., 1987). While it is not possible to change the quality of any plant material, the litter quality can be manipulated by mixing high with low quality organic matter to reduce leaching losses, prolong nutrient availability and synchronize nutrient release with crop demands (Myers *et al*., 1994). Mixing of litters led to a modification of the decomposition rates of individual components in the mixture (Dalias *et al*., 2003). When characteristics of decomposition in litter mixes deviate from responses predicted from single-species decomposition, it is 'non-additive' and if responses in mixes are predictable from component species decaying alone the effect is 'additive' (Gartner and Cardon, 2004). The effect of mixing seems to be more often non-additive that is the decomposition rate of the litter mixtures is either faster or slower than the average rate of the two individual litters (Berglund and Agren, 2011). The effect is synergistic (positive) if the mass loss/nutrient release in litter mixtures is faster/enhanced and antagonistic (negative) if the mass loss/nutrient release is slower/retarded.

To meet the nutrient demand of the crops planted especially by the resource poor farmers, the use of organic materials would be an inevitable practice for a long time to come (Satyanarayana *et al*., 2002). Hence, it is important to understand the processes of mass loss and nutrient release patterns of the individual and mixed leaf litters. This would enable the farmers to manage the organic resources in a manner that would optimise nutrient uptake in crops. Therefore, the aims of the present study were, firstly, to investigate the rate of mass loss and nutrients N, P and K release patterns of commonly used leaf litters of chir pine (*Pinus roxburghii*) and oak (*Quercus griffithii*) in ratios of 100 (alone), 50:50 and 30:70; secondly, to investigate if there is additive or non-additive effect/interaction due to litter mixing in relation to mass and nutrients contents.

MATERIALS AND METHODS

Experimental site: The study was conducted at the research farm of Renewable Natural Resources Development Centre, Bajo (89°15'N, 27°70'E), Wangdiphodrang district in west-central Bhutan from June 10th 2010 till October 31st 2010 for a period of 20 weeks. Soil characteristics of the experimental site were (0-30 cm): soil texture was clay loam with 35% sand, 36% silt and 29% clay, soil pH was 6.18 (1:2.5 water), CEC 13.70 me. 100 g^{-1}, EC 0.03 mS cm^{-1}, C content 1.60%, total N 0.09%, available P 2.72 mg kg^{-1} and exchangeable K 258 mg kg^{-1}. The total rainfall received during the study period was 710 mm and the mean temperature was 24.30°C.

Plant materials preparation: Leaf litters of oak and chir pine were collected from the forests in the study area. The collected leaf litters were chopped into 10-20 mm in length and air dried for a week. Sub-samples weighing 20 g of the leaf litters were put in the oven at 70°C for 48 h; after oven drying they were weighed and dry matter content was calculated. They were ground and analysed to determine their initial nutrient contents N, P and K as well as C:N ratio, lignin, polyphenols and acid detergent fibre.

Decomposition study: Decomposition study was conducted using the litterbag technique. Sixteen grams of leaf litters were used in nylon net bag (2 mm mesh) for the area size of 20×20 cm which was based on 4000 kg ha^{-1} farmyard manure (cattle manure and leaf litters) dry weight (RNRRC/NSSC, 2001). There were five treatments (Table 1) with four replications.

The air-dried leaf litters were mixed thoroughly to make a homogeneous mixture and placed inside the nylon net bags and stitched tightly. The plot layout was a randomized complete block design with eleven litter bags being inserted at 10 cm soil depth for each plot. The litter bags were retrieved from the soil at 1, 2, 4, 6, 8, 12, 16 and 20 weeks. After retrieving, they were washed lightly with running tap water and sun dried for 3 days. Then they were transferred to paper envelopes and oven dried at 70°C for 48 h. Dry weight was determined and a sub-sample was ground and analysed for total N, P and K. At the same time, sub samples of 1 g from each treatment were ashed at 550°C for 6 h to remove soil contaminations. Percent dry weight and nutrient remaining (X) were calculated on ash free basis:

$$\text{Remaining X (\%)} = \frac{W_t}{W_i} \times 100$$

where W_i is the initial dry weight or initial nutrient content and W_t is the oven dry weight or nutrient content at each sampling time.

Interactions in litter mixtures: Interactions of the litters in litter mixtures in relation to mass loss and nutrient content during decomposition were analysed by comparing the observed and predicted values. Predicted values of mass loss/nutrient N, P and K contents were calculated using

Table 1: Five treatments used for the decomposition study

Treatments	Cp:Ok (%)
Chir pine (Cp) alone	100
Oak (Ok) alone	100
Chir pine+Oak	50:50
Chir pine+Oak	30:70
Chir pine+Oak	70:30

the equation: $M_{Pt} = XM_{At}+XM_{Bt}$, where M_{pt} is predicted mass loss/nutrient content, X is proportion of litters used in litter mixtures. In the present study the proportions of chir pine and oak leaf litters used in litter mixtures were 50:50, 30:70 and 70:30, respectively. M_{At} = mass loss/nutrient content from single species 'A' at time 't' and M_{Bt} = mass loss/nutrient content from single species 'B' at time 't' (Gartner and Cardon, 2004). In the present study A is chir pine and B is oak. Interactions in litter mixtures were analysed by plotting the observed and predicted mass loss/nutrient content. A 1:1 line indicates no real interactions (additive effect) while any deviation from this line indicates non-additive which is positive (synergistic) or negative (antagonistic) in nature. In case of nutrient content (presented as nutrient loss in figures), the positive values indicate net mineralization and negative values indicate net immobilization.

Data analysis: Data were analysed using Statistix 8. Data were subjected to linear models analysis of variance pertaining to randomized complete block design (ANOVA). One-factor ANOVA was used to analyse the main effects of the treatments at $p<0.05$ significance level. Graphical presentations and best fit curves were computed for the observed and predicted values (mass loss/nutrient contents) in the litter mixtures using SigmaPlot 8 programme.

RESULTS

Chemical qualities of the leaf litters: Chemical qualities of chir pine and oak leaf litters were different in C:N ratio, N, K and polyphenol contents. Oak leaf litters had lower C:N ratio (37.94) compared to chir pine (76.75). The N content was lower in chir pine (0.52%) than oak (0.86%). While oak leaf litters had higher polyphenol content of 45.20 g kg^{-1} compared to 19.70 g kg^{-1} in chir pine. The K content was higher in chir pine however they had similar P, acid detergent lignin and acid detergent fibre contents (Table 2).

Dry weight remaining (% of the original): Highly significant differences were observed among the treatments during all the weeks. At the end of week 1 and 2, samples from 100 (Ok) treatment lost the maximum weight of about 10.19 and 12.07%, respectively, while the weight losses in other four treatments were less than 3.00%, significantly different from 100 (Ok) treatment ($p<0.001$). At the end of week 4 and 6 again, 100 (Ok) had maximum weight loss significantly different from 100 (Cp), 50:50 (Cp:Ok) and 70:30 (Cp:Ok) treatments ($p<0.001$). Similar trend was observed at the end of week 8, with 100 (Ok) again having the highest mass loss significantly different from the other four treatments ($p<0.001$).

Again from week 12 till the last sampling date, 100 (Ok) followed by 30:70 (Cp:Ok) treatment continued to lose highest weight, significantly different from 100 (Cp), 50:50 (Cp:Ok) and 70:30 (Cp:Ok) treatments ($p<0.001$). Throughout the study period, samples with high proportion of oak (70 and 100%) lost the maximum dry weights (Fig. 1a).

Table 2: Chemical qualities of chir pine and oak leaf litters

		Concentration (%)					
	C:N ratio	N	P	K	ADL	ADF	Polyphenol (g kg^{-1})
Chir pine	76.75	0.52	0.07	0.49	30.47	58.70	19.70
Oak	37.94	0.86	0.08	0.32	28.57	61.27	45.20

ADL: Acid detergent lignin, ADF: Acid detergent fibre

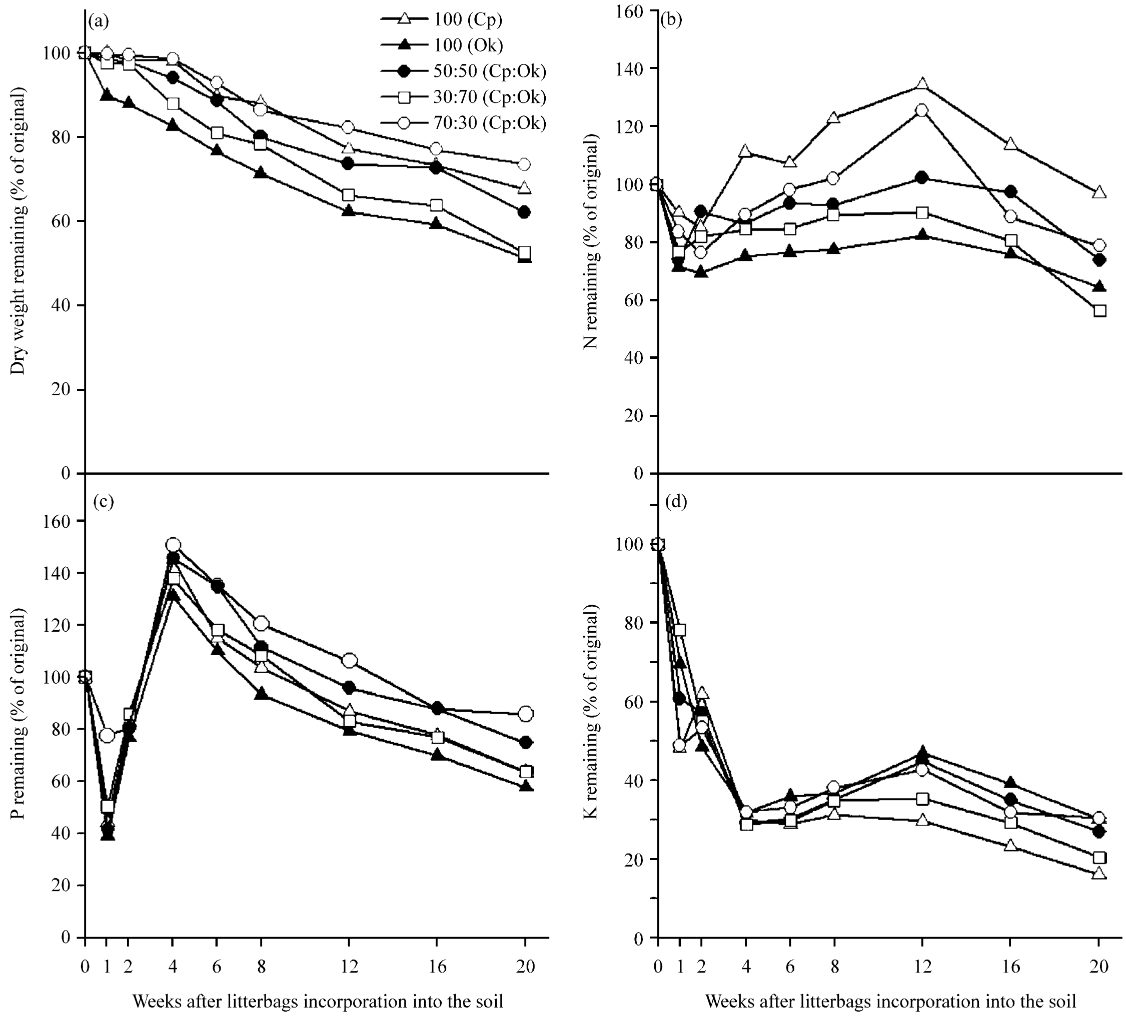

Fig. 1(a-d): (a) Dry weight, (b) N, (c) P and (d) K remaining in the litterbags at different weeks after incorporation into the soil

N remaining (% of the original): Throughout the study, significant differences were observed in N remaining among the treatments. The treatments showed three phases of N remaining, initial decrease followed by fluctuation (increase/decrease) in the middle and decrease towards the later stages. At the end of week 1, 100 (Ok) lost the maximum N (28.5%) significantly different from 100 (Cp) treatment which had the lowest N loss (9.82%) ($p<0.05$). At the end of week 2, 50:50 (Cp:Ok) had the highest N remaining, significantly different from 100 (Ok) treatment with the maximum N loss ($p<0.01$). At the end of week 4, 100 (Cp) immobilized highest N (111.12%), significantly different from the other four treatments ($p<0.001$) and also at week 6, it had the highest N remaining significantly different from 100 (Ok), 50:50 (Cp:Ok) and 30:70 (Cp:Ok) treatments ($p<0.001$).

At the end of week 8, more N was immobilized by 100 (Cp) (122.70%) significantly different from the other four treatments ($p<0.001$). While 100 (Ok) followed by 30:70 (Cp:Ok) continued to lose highest N, at the end of week 12 they were significantly different from 100 (Cp), 50:50 (Cp:Ok) and 70:30 (Cp:Ok) treatments ($p<0.001$). At the end of week 16, again 100 (Ok) had the highest N loss significantly different from 100 (Cp) and 50:50 (Cp:Ok) treatments ($p<0.01$). At the last sampling date, N loss was greatest in 30:70 (Cp:Ok) (43.72%) followed by 100 (Ok), significantly different from 100 (Cp) and 70:30 (Cp:Ok) treatments ($p<0.001$). During this week, 100 (Cp) treatment lost the least N of only about 3.1%. Treatments containing high proportion of chir pine (70 and 100%) showed high immobilization of N; maximum of 134.26% in 100 (Cp) and 125.52% in 70:30 (Cp:Ok) treatments were observed during week 12. At the end of week 20, N release was in the order of 30:70 (Cp:Ok), 100 (Ok)>50:50 (Cp:Ok)>70:30 (Cp:Ok)>100 (Cp) treatments (Fig. 1b).

P remaining (% of the original): Significant differences were found in P remaining among the treatments except week 2. P remaining decreased rapidly at the end of week 1 in the treatments; 70:30 (Cp:Ok) treatment had highest P remaining significantly different from the other four treatments ($p<0.001$). At the end of week 4, all the treatments showed increase in P remaining (>100%) with the highest P remaining again in 70:30 (Cp:Ok) significantly different from 100 (Ok) and 30:70 (Cp:Ok) treatments ($p<0.01$).

At the end of week 6, P remaining decreased in all the treatments compared with week 4, however, it still exceeded 100% with the highest P immobilization observed in 70:30 (Cp:Ok) (135.35%) and 50:50 (Cp:Ok) (134.63%) significantly different from 100 (Cp), 100 (Ok) and 30:70 (Cp:Ok) treatments ($p<0.001$). At the end of week 8, P loss was found only in 100 (Ok) significantly different from the other four treatments ($p<0.001$); though the four treatments showed decrease in P remaining compared to week 6, however immobilization of P still remained.

At the end of week 12, highest P losses were found in 100 (Ok) followed by 30:70 (Cp:Ok) significantly different from 50:50 (Cp:Ok) and 70:30 (Cp:Ok) treatments ($p<0.01$). At the end of week 16 and the last sampling date, P loss was greatest in 100 (Ok) significantly different from 50:50 (Cp:Ok) and 70:30 (Cp:Ok) treatments ($p<0.05$, $p<0.001$); lowest P loss was found in 70:30 (Cp:Ok) treatment. At the end of week 20, P release was in the order of 100 (Ok), 100 (Cp), 30:70 (Cp:Ok)>50:50 (Cp:Ok)>70:30 (Cp:Ok) treatments (Fig. 1c).

K remaining (% of the original): The K remaining also showed significant differences among the treatments with the exception in week 2, 4 and 8. Similar to P remaining, K decreased rapidly at the end of week 1 in all the treatments; lowest K remaining was found in 100 (Cp) significantly different from 100 (Ok) and 30:70 (Cp:Ok) treatments which had the highest K remaining ($p<0.001$). At the end of week 6, 100 (Cp) still had the highest K loss followed by 30:70 (Cp:Ok) significantly different from 100 (Ok) treatment ($p<0.05$). From week 12 till the last sampling date, 100 (Cp) continued to lose the maximum K significantly different from 100 (Ok), 50:50 (Cp:Ok) and 70:30 (Cp:Ok) treatments ($p<0.01$, $p<0.001$). In contrast to N and P, more than 50% of K was lost in all the treatments at the last sampling date. At the end of week 20, K release was in the order of 100 (Cp), 30:70 (Cp:Ok)>50:50 (Cp:Ok), 100 (Ok), 70:30 (Cp:Ok) treatments (Fig. 1d).

Interactions in litter mixtures

Observed and predicted mass loss: Good agreement between the observed and predicted mass loss (%) with R^2 ranging from 0.69-0.93 were found in the litter mixtures ($p<0.01$, $p<0.05$;

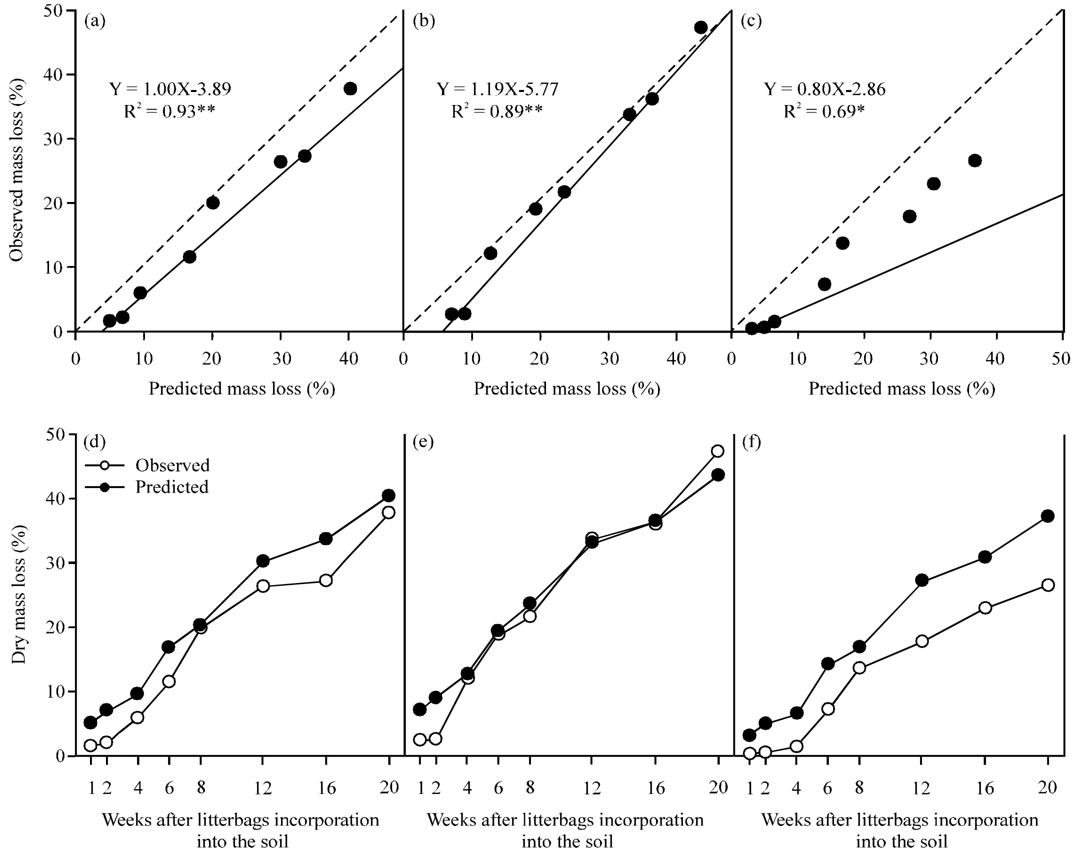

Fig. 2(a-f): Relationship between predicted and observed dry mass loss (%) in (a) 50:50 (Cp:Ok), (b) 30:70 (Cp:Ok) and (c) 70:30 (Cp:Ok) treatments. Dashed line (45°) indicates observed and predicted values being equal, change in predicted and observed dry mass loss (%) in, (d) 50:50 (Cp:Ok), (e) 30:70 (Cp:Ok) and (f) 70:30 (Cp:Ok) treatments. *,**Significant at $p<0.05$ and $p<0.01$, respectively

Fig. 2a-c). The figure indicated non-additive interactions in the litter mixtures (Fig. 2d-f). During all the sampling dates, antagonistic interactions (observed<predicted) were observed in 50:50 (Cp:Ok) and 70:30 (Cp:Ok) treatments. The 30:70 (Cp:Ok) treatment though showed antagonistic interactions, the observed and the predicted values were very close and at the end of week 20, it shifted to synergistic interaction. This showed that high proportion (70%) of oak has enhanced the mass loss in the litter mixture while chir pine has retarded decomposition when mixed in higher proportion (50 and 70%).

Observed and predicted N loss: The observed and predicted N loss (%) also showed non-additive interactions in the litter mixtures ($p<0.01$, $p<0.05$; Fig. 3a-c). While both antagonistic and synergistic interactions were observed in the litter mixtures (Fig. 3d-f), more synergistic interactions were found in 30:70 (Cp:Ok) treatment. At the last sampling date all the treatments presented synergistic interaction (observed>predicted) indicating enhanced N mineralization at the later stages of decomposition in all the litter mixtures. There is a clear indication that mixing oak with chir pine has enhanced N mineralization in the litter mixtures.

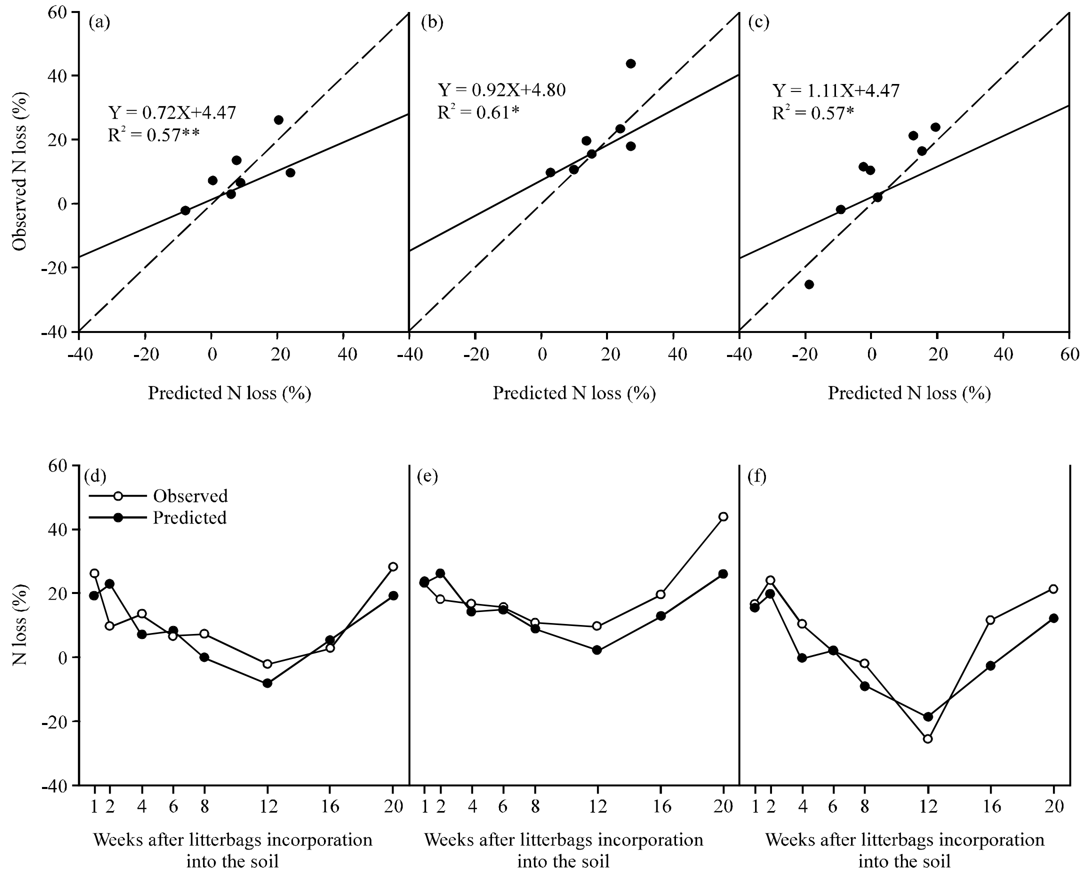

Fig. 3(a-f): Relationship between predicted and observed N loss (%) in, (a) 50:50 (Cp:Ok), (b) 30:70 (Cp:Ok) and (c) 70:30 (Cp:Ok) treatments. Dashed line (45°) indicates observed and predicted values being equal, change in predicted and observed N loss (%) in, (d) 50:50 (Cp:Ok), (e) 30:70 (Cp:Ok) and (f) 70:30 (Cp:Ok) treatments. *,**Significant at $p<0.05$ and $p<0.01$, respectively

Observed and predicted P loss: Similar to mass and N loss, in case of P also, the litter mixtures showed non-additive interactions during all the sampling dates ($p<0.01$, $p<0.05$; Fig. 4a-c). Interestingly, P followed a different pattern than that of N content. The observed and predicted P loss were almost same (58.62 vs. 58.17%, 19.45 vs. 20.09%) in 50:50 (Cp:Ok) treatment at week 1 and 2, respectively. During all the sampling dates, the observed values were lower than the predicted in 30:70 (Cp:Ok) treatment. The 70:30 (Cp:Ok) treatment showed synergistic interaction (small) (19.53 vs. 18.87%) only at week 2 while the remaining weeks showed antagonistic interactions. However, from week 4 till the last sampling date, all the litter mixtures showed antagonistic interactions (Fig. 4d-f). Nonetheless, in general the observed values in litter mixture with high proportion of oak (70%) were closer to the predicted values compared to litter mixtures with either equal or less oak (50 and 30%). Unlike N, mixing oak and chir pine had slow P mineralization.

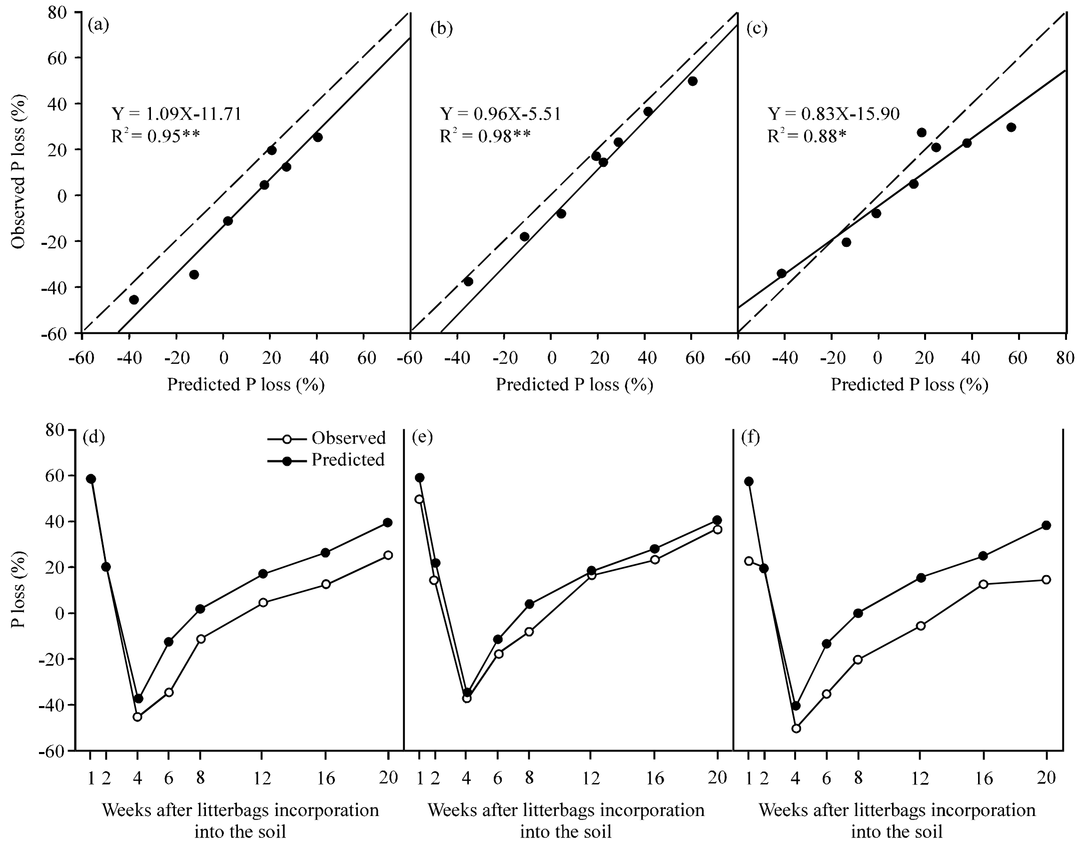

Fig. 4(a-f): Relationship between predicted and observed P loss (%) in, (a) 50:50 (Cp:Ok), (b) 30:70 (Cp:Ok) and (c) 70:30 (Cp:Ok) treatments. Dashed line (45°) indicates observed and predicted values being equal, change in predicted and observed P loss (%) in, (d) 50:50 (Cp:Ok), (e) 30:70 (Cp:Ok) and (f) 70:30 (Cp:Ok) treatments. *,**Significant at $p<0.05$ and $p<0.01$, respectively

Observed and predicted K loss: Similar to N and P, K also showed non-additive interactions ($p<0.01$; Fig. 5a-c). The litter mixtures showed both synergistic and antagonistic interactions (Fig. 5d-f). Synergistic interactions (small) were found in 50:50 (Cp:Ok) treatment at week 4 and 6, while antagonistic interactions were found during the remaining weeks. More synergistic interactions were observed in litter mixture with high proportion of oak (70%); except for week 1 and 2, the observed values from week 4 till the last sampling date were higher than the predicted values though the difference was very small at week 8. While at the later weeks in the litter mixtures with either equal or high proportion of chir pine (50 and 70%), the observed values were lower than predicted. The results indicate that higher proportion of oak (70%) enhances K mineralization in litter mixtures.

DISCUSSION

C:N ratio is one of the most widely used litter quality parameters in predicting rate of litter decomposition and nutrient release (Heal *et al.*, 1997). Kaewpradit *et al.* (2008) found using N rich

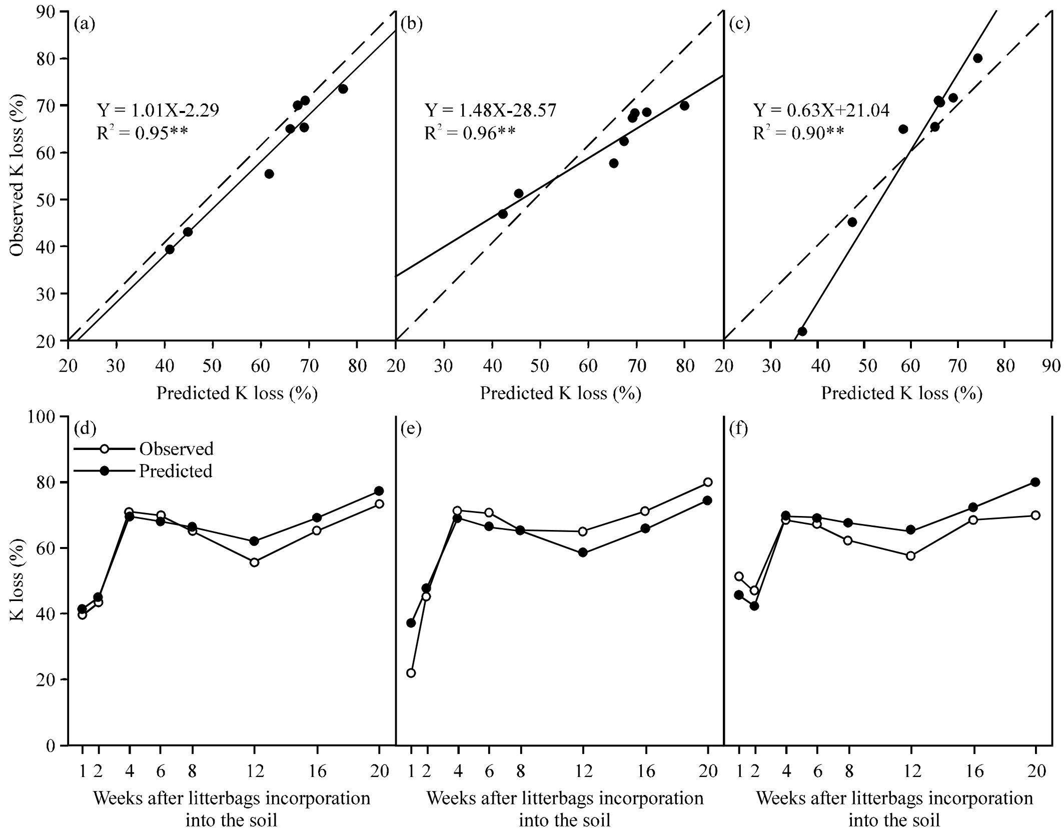

Fig. 5(a-f): Relationship between predicted and observed K loss (%) in, (a) 50:50 (Cp:Ok), (b) 30:70 (Cp:Ok) and (c) 70:30 (Cp:Ok) treatments. Dashed line (45°) indicates observed and predicted values being equal, change in predicted and observed K loss (%) in, (d) 50:50 (Cp:Ok), (e) 30:70 (Cp:Ok) and (f) 70:30 (Cp:Ok) treatments. **Significant at p<0.01, respectively

groundnut residues led to rapid net N mineralization while high C:N ratio rice straw resulted in initial N immobilization and concluded that the observed processes were controlled by either the N content or C:N ratio of the residues. Taylor *et al.* (1989) also reported that N content and the C:N ratio were the best predictors of decomposition rather than lignin:N ratio. Similarly, the results from the present study confirmed that high C:N ratio and low N content in chir pine retarded the decomposition process while the low C:N and high N content enhanced the mass loss and nutrient release in oak. In addition to the litter quality as reported by Heath and Arnold (1966) slow decomposition in chir pine needles must be also due to their hard texture and the presence of astringent substances such as polyphenols and gallic acids which make them less favourable to attack by the soil microfauna. Substantial immobilization of N and P were observed in litter mixtures with high proportion of chir pine (70 and 100%). Similar pattern of N and P mineralization/immobilization are reported in several studies (Isaac and Nair, 2005; Pandey *et al.*, 2007; Suvannang *et al.*, 2010). Such differences in nutrient concentrations (mineralization/immobilization) could be due to decomposer communities prevalent under different ecosystems (Pandey *et al.*, 2007) and microbial immobilization (Isaac and Nair, 2005). Colonization by fungi mycelium observed in the litters during the study, especially in the litter mixtures containing chir pine could have attributed to more immobilization of N and P in chir pine leaf litters than oak.

The trend shown by K in the present study is in agreement with Osono and Takeda (2004) who reported initial fast leaching of K from decomposing litters followed by a late phase of fluctuation in concentration. The rapid release of K could be due to its high mobility compared to other macro nutrients. K is not strongly bonded to complex organic molecules in plant tissues, hence microbial activities are not required for its release from detritus (Alexander, 1977).

In their review on decomposition dynamics in mixed-species leaf litters, Gartner and Cardon (2004) observed non-additive patterns of mass loss in 67% of tested mixtures implying the mass loss often increased (though not always) in litter mixtures. Similarly, the present study found non-additive synergistic and antagonistic patterns of mass loss and nutrient contents in the litter mixtures. Mixing different quality litters could change the quantity, composition and activities of decomposer organisms which partly contribute to the non-additive effects of litter mixtures (Liu *et al.*, 2007). However, the study findings do not support the findings of Prescott *et al.* (2000) who reported either 'no effect' or a 'slight suppression' of decomposition when litters were mixed and concluded that there was no evidence that addition of broadleaf litter hastened decomposition of needle litters.

In case of P content, antagonistic effects of mixing were more pronounced in all the litter mixtures, however observed P values in the litter mixture with high proportion of oak (70%) were closer to the predicted values compared to litter mixtures with either 30 or 50% oak. This indicates a better release of P when high proportion of higher quality litter (oak) is mixed with lower quality litter (chir pine). Similar to N and P, K also showed both non-additive synergistic and antagonistic interactions. The study results are in agreement with earlier studies where non-additive interactions are reported in many of the litter mixtures (Ball *et al.*, 2009).

The synergistic effects during residue mixture decomposition may be attributed to the nutrient transfer among litter types e.g. nitrogen transfer from nutrient rich litter (*Quercus*) to nutrient-poor litter (*Pinus*) and due to possible improved microclimate of the decay environment due to different physical structures of the litters (Salamanca *et al.*, 1998) and enhanced faunal activity (Chapman *et al.*, 1988). Slower decomposition/antagonistic effect in litter mixtures is due to the release of inhibitory compounds such as phenolics and tannins (Fyles and Fyles, 1993; Salamanca *et al.*, 1998). Mao and Zeng (2012) reported that mixing tree leaf litters and crop residues with unequal proportions can potentially be used to manipulate residue decomposition and regulate the timing of nutrient availability in agroforestry systems. Mixing more of higher quality litter with lower quality litter, as done in the present study by mixing higher proportion of oak (70%) with chir pine (30%), is considered as the optimum litter mixture, this agrees with the findings of Salamanca *et al.* (1998) who also reported the ratio of 25:75 of *Pinus:Quercus* to be the optimal mixture effect.

CONCLUSION

High nutrient immobilizing nature of chir pine found in the present study is advantageous for prolonged nutrient availability. Among the litter mixture treatments, mixing 70% oak with 30% chir pine is found to be the optimum litter mixture. Non-additive interactions of the litter mixtures indicate the possibility of synchronising nutrient release and plant nutrient uptake through litter manipulation. Thus, the efficient use of organic nutrients through litter mixture manipulations will contribute towards sustainable soil fertility management, increase crop productivity and reduce the cost of production for farmers in developing countries.

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