J. For. Res. (2018) 29(3):593–599
https://doi.org/10.1007/s11676-017-0450-3

ORIGINAL PAPER

Assaying the allelopathic effects of *Eucalyptus camaldulensis* in a nursery bed incorporated with leaf litter

Romel Ahmed[1] · **Mohammad Shafioul Alam**[2] · **Farid Uddin Ahmed**[3] · **M. K. Hossain**[4]

Received: 23 July 2016 / Accepted: 20 October 2016 / Published online: 25 July 2017

Abstract Allelopathic effects of *Eucalyptus camaldulensis* Dehnh. were confirmed in Petri dish and pot experiments in our previous studies. However, the degree to which such effects under controlled experiments exist in more complex ecological settings remains to be tested. Thus, the present study was carried out by incorporating different proportions of ground litter of *E. camaldulensis* in soil. The growth of three agricultural crops: falen (*Vigna unguiculata* (L.) Walp.), chickpea (*Cicer arietinum* L.), and arhor (*Cajanus cajan* (L.) Millsp.), and two tree species, kala koroi (*Albizia procera* (Roxb.) Benth.) and ipil ipil (*Leucaena leucocephala* (Lam.) de Wit) were tested. There were inhibitory effects of leaf litter on germination, shoot and root growth, leaf number, and collar diameter as well as a reduction of nodulation by legume crops (25–80% reduction). The extent of the effects was dependent on the proportion of leaf litter, the species and the type of traits. In contrast to shoot growth, the effect on root growth was more severe. No effect on germination was found with the agriculture crops while the two tree species showed reduced germination. The effect was greater in the presence of higher proportions of leaf litter mixed in soil while in some cases lower proportions stimulated growth. Not all species were suppressed; *A. procera*, *C. cajan*, *V. unguiculata* showed compatible growth while *C. arietinum* and *L. leucocephala* were found incompatible. This study provides evidence that *E. camaldulensis* has allelopathic potential under field conditions and a careful selection of associated crops in agroforestry systems is highly recommended.

Keywords Allelopathy · *Eucalyptus camaldulensis* · Inhibitory effects · Germination · Growth · Nodulation

Introduction

Allelopathy is a well-known mechanism of plant-to-plant interaction exerting adverse effects on ecosystem structure and functions (Powell et al. 2013; Rice 1984; Si et al. 2013; Yuan et al. 2013). Association and dissociation patterns between certain species in an ecosystem may be governed by direct competition for necessary growth factors or through addition of allelopathic chemicals into the rhizosphere (Ashrafi et al. 2008; Bargali and Bargali 2000a, b; Einhelling 1996). The concept of allelopathy has received increased attention in the context of successful plant invasions over resource competition (Del Fabbro et al. 2014). The evidence of adverse allelopathic effects on germination, growth, development, and survival, nitrogen fixation and/or selective mycorrhizal fungi through the release of alleochemicals via leaching, litter decomposition, root exudation and/or direct volatilization has been shown in several studies (Abhilasha et al. 2008; Ahmed

---

The online version is available at http://www.springerlink.com

Corresponding editor: Tao Xu.

✉ Romel Ahmed
romel-fes@sust.edu

[1] Department of Forestry and Environmental Science, Shahjalal University of Science and Technology, Sylhet 3114, Bangladesh

[2] Ministry of Public Administration, Teknaf, Coxsbazar, Dhaka 4761, Bangladesh

[3] Arannayk Foundation House 21, Western Road, DOHS, Banani, Dhaka 1206, Bangladesh

[4] Institute of Forestry and Environmental Science, University of Chittagong, Chittagong 4331, Bangladesh

et al. 2004, 2007a, 2008; Hoque et al. 2003a, b; Inderjit 2005; Sun and He 2010; Uddin et al. 2007; Yang et al. 2007; Yuan et al. 2013). Consequently, there is a growing interest in studying allelopathy in suitable species combinations for commercial agroforestry (Ahmed et al. 2007b, 2008). *Eucalyptus* spp. are grown world-wide in association with agricultural crops, as windbreaks around orchards, and as avenue trees on farms (Ahmed et al. 2007b; Attiwill 1979; Bargali et al. 1992a, b, 1993; Bradstock 1981; Hasanuzzaman et al. 2004). Various species have been planted in many countries in preference over local species, owing largely to their versatility in adapting to a wide spectrum of climate and soil conditions, and in providing reasonable financial returns on a short rotation, i.e., 5–6 years. The wood of many species is suitable for a wide variety of uses (Davidson 1985). *Eucalyptus* spp. were introduced into Bangladesh in the nineteenth century, probably in the 1930's, in the eastern part of the country by tea planters as ornamental trees (Davidson and Das 1985). Later on, eucalypts were spread throughout the country in a haphazard manner by botanists, foresters, gardeners and tree planters (Hassan 1994). A total of 18,900 ha of plantations are under eucalyptus, 7% of the total plantation area in the country (Hossain and Hoque 2013). The plantations supply a vital demand for fuelwood, poles and posts for domestic use (Ahmed and Akhter 1995). Nevertheless, a controversery over the last few decades has developed as to whether *Eucalyptus* spp. are good or bad (Ahmed et al. 2008; Shiva and Bandyopadhyay 1983). They have been considered as rivals and competitors to endemic flora and environmentally unfriendly to Bangladesh (Ameen 1999), even though data is not enough to support this contention. There is a directive from the Government not to plant these species further (Letter of Ministry of Environment and Forests No. (Gen-3) 50/93/250 of dated 18.04.1995). In contrast, leading forestry and agroforestry experts and scientists have concluded that eucalypts may be suitable species for afforestation and reforestation in denuded areas and on marginal lands, in roadside plantations, and in agroforestry programs (Amin et al. 1995).

The allelopathy of eucalypts is considered the main cause for the reduction of biodiversity and the numbers of plantation forbs and graminoids, and reduced productivity of adjoining crops (Zhang et al. 2010). Our previous research supports the same phenomena of allelopathic effects on crops (Ahmed et al. 2004, 2007c, 2008). However, most of the evidence mainly relies on bioassays and pot experiments under controlled conditions. The major drawback of allelopathic research is the single application of extracts in most of the bioassay studies, which excludes abiotic and biotic manipulators of potential allelochemicals that would be encountered in the field (Ens et al. 2009). In fact, various environmental factors including temperature, light, soil, precipitation, nutrients, water availability, and understory vegetation are important to consider as allelopathy greatly relies on them (Ahmed et al. 2008; Catherine et al. 2006, 2008; Khan et al. 1999). Past criticisms of allelopathic studies were based on the confusion between phytotoxicity and allelopathy and the failure to incorporate soil media, and the results were therefore regarded as lacking field relevance. Therefore, we hypothesized that a test of allelopathic effects could be different from a fully controlled situation if experiments were done in the soil where there is a chance of interaction between biotic and abiotic factors that would mimic nature. Thus, the present experiment was performed in the field to test whether the allelopathic effects of *Eucalyptus camaldulensis* shown earlier under controlled conditions (Ahmed et al. 2004, 2007c, 2008) are also detectable under ecologically more relevant soil-leaf litter mix conditions.

Materials and methods

The research was carried out in the nursery of the Institute of Forestry and Environmental Sciences, Chittagong University in a randomized block design with five replications for each treatment. Leaf litter from 8-year-old *E. camaldulensis* was collected, air-dried and ground. The nursery bed was 2 m × 2 m separated by a 100 cm deep trench and leveled. All weeds and other debris were cleared. The bed was thoroughly prepared by adding 30 cm topsoil collected from a barren hillside and mixed with the ground leaf litter in the following proportions:

T_0 = Seeds of crops grown in bed with barren hillside soil with no litter added (Control),
T_1 = Seeds of crops grown in bed mixed with litter of 10 gm/m^2 (100 kg/ha),
T_2 = Seeds of crops grown in bed mixed with litter of 50 gm/m^2 (500 kg/ha),
T_3 = Seeds of crops grown in bed mixed with litter of 100 gm/m^2 (1000 kg/ha),
T_4 = Seeds of crops grown in bed mixed with litter of 150 gm/m^2 (1500 kg/ha) and
T_5 = Seeds of crops grown in bed mixed with litter of 200 gm/m^2 (2000 kg/ha)

The litter application rates varied from 100 to 2000 kg per hectare, which represented an average accumulation of 1028 kg/ha/year litter fall in an 18-year-mixed plantation (Haque 2013). After adding the litter mix soil, the bed was lightly irrigated and kept under a polythene sheet for a month. Seeds of the crops were sown after 3 months to allow the leaching and mixing of the released allelochemicals which were subjected to the exposure of other biotic and abiotic interactions. The agricultural and tree crops selected were falen (*Vigna unguiculata*), chickpea (*Cicer arietinum*), arhor (*Cajanus cajan*), kala koroi (*Albizia procera*) and ipil ipil (*Leucaena leucocephala*). The agricultural crops were harvested after one and half months and the tree crops after two and half months.

The seed was considered germinated when the radicle emerged and germination was recorded daily up until the last radicle protruded. Watering and weeding were done when required. All growth parameters such as shoot and root length, collar diameter, lateral roots, nodule number and size, leaf, leaflet number, and root diameter were recorded. For the calculation of the degree of inhibitory effect on root and shoot elongation and collar diameter, the percentage compared to the control was calculated as per the formula developed by Surendra and Pota (1978). Ducan's Multiple Range Test (DMRT) using the SPSS package was used to analyze the data to a significance level of 1%.

Results

Germination

Germination of the agriculture and tree crops under different proportions of leaf litter mixture with the soil is shown in Table 1. All three crop species showed no effect even with the higher proportion of leaf litter compared to the controls. In contrast, germination of the two tree species was sensitive to the exposure to leaf litter and sensitivity progressively increased with the increase in litter. Of the two tree species, the performance of *L. leucocephala* was poorest (Table 1).

Shoot and root length

Unlike germination, the response of shoot and root growth of all the seed material significantly varied with the amount of leaf litter. The higher the percentage of leaf litter, the higher the inhibitory effect on all species, except the root growth of *C. arietinum* which was stimulated (Table 3) even though shoot growth was reduced (Table 2). Significant reduction in root growth of all other species was found with the T_5 treatment followed by a descending order of leaf litter component. Compared with the shoot growth, the effect on root growth was more severe. With the T_5 treatment, the reduction of primary root development of *C. cajan*, *V. unguiculata, A. procera* and *L. leucocephala* was 22.5, 56.93, 42.1, and 45.5%, respectively while that of shoot growth of those crops was 8.3, 40.61, 2.8 and 25.2%, respectively. Compared to controls, shoot growth of *A. procera* was less affected amongst the all species and was stimulated at the lower levels of litter (Table 2). However, root growth of *A. procera* was profoundly inhibited as was *V. unguiculata* and *L. leucocephala*, while root growth of *C. cajan* was less affected after *C. arietinum* (Table 3).

Collar diameters

Collar diameters of seedlings with different proportions of leaf litter showed no statistically significant variations except for *L. leucocephala* (Table 4). Collar diameters were statistically different and suppressed with increasing of levels of litter. All other crops responded differently, showing both inhibited and stimulated growth with different treatments. The highest inhibitory effect (−32%) was found with *C arietinum* seeds with T_4 treatment, while *A. procera* was the lowest (−1.1%) at the same treatment. The greatest stimulatory effect (+14.9%) was with *V. unguiculata* seeds with the T3 treatment and the lowest (+0.7%) with *A. procera* and the T_1 treatment (Table 4).

Leaf and nodule number

There was no consistent pattern of the effect of litter on leaf number of crops (Table 5). A lower proportion of litter showed stimulatory effects while the highest dosage

Table 1 Germination percentage of crop/tree species to the application of proportions of leaf litter

Treatments	Germination of crop seeds				
	C. arietinum	*C. cajan*	*V. unguiculata*	*A. procera*	*L. leucocephala*
T_0	48 a	58 a	93 a	73 a	45 b
T_1	43 a	57 a	92 a	56 b	65 a
T_2	45 a	58 a	93 a	70 a	42 b
T_3	43 a	56 a	83 a	53 b	25 d
T_4	45 a	56 a	77 a	52 b	30 d
T_5	45 a	56 a	79 a	55 b	38 c

Values followed by the same letters are not significantly different according to Duncan Multiple Range Test (DMRT)

Table 2 Shoot lengths (cm) with different proportions leaf litter

Treatments	Shoot length of crop seeds				
	C. arietinum	*C. cajan*	*V. unguiculata*	*A. procera*	*L. leucocephala*
T_0	40.22 a	56.44 a	25.44 a	17.61 a	77.58 a
T_1	32.33 a (−19.6)	54.78 a (−2.9)	20.00 bc (−21.4)	18.11 a (+2.8)	62.89 ab (−18.9)
T_2	32.22 a(−19.9)	55.55 a (−1.6)	17.89 b (−29.7)	18.11 a (+2.8)	62.78 ab (−19.1)
T_3	33.44 a (−16.8)	53 ba (−6.1)	21.67 b (−14.8)	15.5 b (−11.9)	59.56 b (−23.2)
T_4	25.82 a (−35.8)	46.72 c (−17.2)	18.44 b (−27.5)	17.33 ab (−1.6)	61.72 ab (−20.4)
T_5	28.55 a (−29.0)	51.78 ab (−8.3)	15.11 c (−40.6)	17.11 ab (−2.8)	58.0 b (−25.2)

Values followed by the same letters are not significantly different according to Duncan Multiple Range Test (DMRT), while values in parenthesis indicates stimulatory (+) or inhibitory (−) effects in comparison to control (To) treatments

Table 3 Root lengths (cm) of crop seeds with different proportions leaf litter

Treatments	Root lengths of crop seed				
	C. arietinum	*C. cajan*	*V. unguiculata*	*A. procera*	*L. leucocephala*
T_0	10.74 ab	13.89 a	33.67 a	22.17 a	40.0 a
T_1	12.22 a (+13.3)	11.0 b (−20.8)	16.89 b (−49.8)	13.11 cd (40.8)	27.78 bc (−30.5)
T_2	10.19 b (−5.7)	11.94 b (−14.0)	16.33 bc (−51.5)	11.72 d (47.1)	30.72 bc (−23.2)
T_3	9.64 b (−10.2)	12.0 b (−13.6)	15.83 bc (−52.9)	17.78 b (−19.8)	32.67 ab (−18.3)
T_4	10.61 ab (−1.2)	12.0 b (−13.6)	17.5 b (−48.0)	14.27 c (−35.6)	22.0 c (−45.0)
T_5	11.44 ab (+6.5)	10.77 b (−22.5)	14.5 c (−56.9)	12.83 cd (−42.1)	21.78 c (−45.5)

Values in the columns followed by the same letters are not significantly different according to Duncan Multiple Range Test (DMRT) while values in parenthesis indicates stimulatory (+) or inhibitory (−) effects in comparison to control (To) treatments

Table 4 Collar diameter of crop/tree species on the application of different proportions leaf litter

Treatments	Collar diameter (mm) of crops				
	C. arietinum	*C. cajan*	*V. unguiculata*	*A. procera*	*L. leucocephala*
T_0	3.28 a	3.9 a	4.09 a	2.73 a	6.38 a
T_1	3.61 a (+10.1)	34 a (−12.8)	3.71 a (−9.3)	2.75 a (+0.7)	5.91 ab (−7.4)
T_2	3.35 a (+2.1)	3.83 a (−1.8)	4.31 a (+5.4)	2.57 a (−5.9)	5.69 b (−10.8)
T_3	2.29 a (−30.2)	3.79 a (−2.8)	4.7 a (+14.9)	2.49 a (−8.8)	5.63 ab (−11.7)
T_4	2.23 a (−32.0)	3.75 a (−3.8)	4.37 a (+6.8)	2.7 a (−1.1)	5.42 b (−15)
T_5	2.81 a (−14.3)	3.83 a (−2.6)	4.07 a (−0.5)	2.3 a (−15.7)	4.54 c (−28.8)

Values followed by the same letters are not significantly different according to Duncan Multiple Range Test (DMRT) while values in parenthesis indicate the stimulatory (+) or inhibitory (−) effects

reduced the leaf number of all species except *V. unguiculata*. There was an inhibitory effect on nodulation of plants (Table 6), the trend increased with increasing of leaf litter. However, different plants responded differently to different treatments. *V. unguiculata* and *A. procera* had a higher number of nodules in control treatments, and then showed a significant uneven decreasing trend from treatment T_1 onwards. Nodulation of *C arietinum* and *C. cajan* was stimulated by the T_1 and T_2 treatments and then decreased. The average highest number of nodules (32.11) was recorded with *A. procera* under the control treatment while the lowest (0.33) was by *C. arietinum* with the T_5 treatment (Table 6). Nodulation in *L. leucocephala* was also observed but the nodules were distributed in such a way that they were impossible to count. In fact, nodule number in *L. leucocephala* was more than with any other seedlings.

Table 5 Number of leaves of crops with application of different proportions litter

Treatments	Leaf numbers of crops				
	C. arietinum	*C. cajan*	*V. unguiculata*	*A. procera*	*L. leucocephala*
T_0	50.33 b	22.57 a	18.67 ab	5.55 ab	22.83 b
T_1	57.67 a	20.44 b	14.33 c	6.22 ab	30.33 a
T_2	46.55 d	20.12 b	19.44 a	7.11 a	22.50 b
T_3	47.88 cd	20.50 b	17.22 b	6.00 ab	18.33 c
T_4	49.44 bc	20.22 b	18.55 ab	6.22 ab	24.17 b
T_5	35 e	19.11 b	18.67 ab	4.33 b	14 d

Values in columns with the same letter are not significantly different according to Duncan Multiple Range Test (DMRT)

Table 6 Nodule numbers of crops with the application of different proportions leaf litter

Treatments	Nodule number of crops			
	C. arietinum	*C. cajan*	*V. unguiculata*	*A. procera*
T_0	2 ab	6.67 ab	14.22 a	32.11 a
T_1	2.5 a	7.5 a	6.11 b	22.27 bc
T_2	3 a	6.88 ab	6.44 b	23.44 c
T_3	1.3 ab	5.1 bc	6.89 b	24.67 c
T_4	1.3 ab	5.33 bc	6.44 b	24.55 c
T_5	0.03 b	3.5 bc	4.78 b	16 d

Values in the columns followed by the same letter are not significantly different according to Duncan Multiple Range Test (DMRT)

Discussion

This study has shown that soil mixed with *E. camaldulensis* leaf litter exerts negative effects on some tree species and agricultural crops, as demonstrated in vitro assays (Ahmed et al. 2004, 2007c, 2008). We assumed that the effect is not due to the slow decomposition of Eucalypt leaf litter (Bargali et al. 1993) but rather it could be attributed to the release of phytotoxic compounds. Many studies have documented that eucalypt litter could produce allelochemicals; for example, Zhang et al. (2010) identified 28 allelopathic compounds in *E. grandis* roots that are structurally similar to those reported to inhibit plant germination and growth (Djurdjevićet al. 2008; Nishimura et al. 1982; Rice 1984; Zhang et al. 2007). The negative impact of *Eucalyptus* species on undergrowth is evident from several comprehensive ecological studies; for instance, Bargali et al. (1992a, b) found a significant decrease in herb biomass and nutrient dynamics under a *Eucalyptus* plantation which progressively increased with plantation age from 2 to 8 years. We rule out the possible role of nutrient dynamics on the reduced growth of the crops, as the effect was compared to the control treatment where only soil was added.

The inhibitory effect of *Eucalyptus* leaf litter on nodulation supports earlier findings on the suppression of nitrification and/or nitrifiers in soils with a eucalypt cover (Adams and Attiwill 1986; Jones and Richards 1977). Monoterpenes which are characteristic of eucalypt leaves were shown to inhibit nitrification in laboratory bioassays (Courtney et al. 1991; Ward et al. 1997; White 1986, 1991; Wood 1996). In agreement with previous results (Ahmed et al. 2004, 2007a, 2008; Ballester et al. 1982; Hoque et al. 2003a), we found the effects on the crops were concentration-dependent, increasing with an increase in litter, resulting in significantly smaller lengths of roots and shoots of target species compared to controls, with higher litter applications. This suggests that potential allelopathic effects could be more pronounced in areas with low or erratic rainfall due to relative higher concentrations of allelochemical substances (May and Ash 1990). In addition, relatively higher germination rates and early growth of the crop species were observed with lower quantities of litter, which was also corroborated by other studies (Ahmed et al. 2004, 2007c, 2008; Hong et al. 2004; Nektarios et al. 2005; Reigosa et al. 2000). The reasons are unclear and further research needs to be carried out. One explanation might be the small amount of nutrients brought by the litter partly contributes to the stimulatory effects (Khan et al. 1999). These effects were not consistent with all crops, nor were all the traits equally sensitive, as germination of the crops showed no effect while the tree species showed reduced germination. *C. arietinum* showed no effect on root growth but shoot growth was inhibited with the increase of litter applications.

The methodological approach of the present study is more robust than laboratory bioassays or other controlled experiments lacking complex ecological settings (Jandová et al. 2015). Methodological inadequacies that include the use of bioassays, insufficient controls and the lack of convincing field studies has raised the question of conclusions regarding the field relevance of alleopathy (Keeley 1988; Stowe 1979). The presence of bioactive allelochemicals does not necessarily mean they have similar effects under both laboratory and field conditions. Exudates or leachates are much lower under natural conditions than in vitro because they are subject to absorption on soil particles as well as to chemical and microbial decomposition (Kaur et al. 2009; Lankau 2010). It is therefore equally important to carry out allelopathy tests adopting more ecologically relevant approaches along with in vitro bioassays. Our present study confirms the allelopathic effects of *Eucalyptus camaldulensis* in soil conditions where there was ample interaction between numerous biotic and abiotic factors, and thus representing the effect of more natural conditions. However, further research should be carried out using the soil of different ages of *Eucalyptus* plantations to see how reproducible the results are.

Acknowledgements The authors gratefully acknowledge the comments and valuable suggestions of anonymous reviewers to improve the quality of the article. We wish to thank Mr. Abdur Rahman, the gardener of Nursery at the Institute of Forestry and Environmental Sciences, Chittagong University for his help in conducting the experiments.

References

Abhilasha D, Quintana N, Vivanco J, Joshi J (2008) Do allelopathic compounds in invasive *Solidago canadensis* s.l. restrain the native European flora? J Ecol 96:993–1001

Adams MA, Attiwill PM (1986) Nutrient cycling and nitrogen mineralization in eucalypt forests of south-eastern Australia. I. Nutrient cycling and nitrogen turnover. Pl Soil 92:319–339

Ahmed FU, Akhter S (1995) Problems and prospects of *Eucalyptus*. In: Amin SMR, Ali MO, Fattah MIM (eds.), *Eucalyptus* in Bangladesh, Proceedings of the National Seminar held at Bangladesh Agricultural Research Council, Dhaka on April 16.1994, pp 42–53

Ahmed R, Uddin MB, Hossain MK (2004) Allelopathic effects of leaf extracts of *Eucalyptus camaldulensis* Dehn. on agricultural crops. Bangladesh. J Bot 33(2):79–84

Ahmed R, Redowan M, Uddin MS, Hossain MK (2007a) A pot experiment to evaluate the allelopathic potential of leaf extracts of *Eucalyptus camaldulensis* on five common agricultural crops. Int J Sustain Agric Technol 5(3):280–285

Ahmed R, Redowan M, Uddin MS, Hossain MK (2007b) *Eucalyptus* as a agroforestry component in the homestead and agricultural field of Sitakunda, Bangladesh. Int J Sustain Agric Technol 3(3):46–51

Ahmed R, Uddin MB, Khan MS, Mukul SA, Hossain MK (2007c) Allelopathic effects of *Lantana camara* L. on germination and growth behavior of some agricultural crops. J For Res 18(4):301–304

Ahmed R, Hoque ATMR, Hossain MK (2008) Allelopathic effects of leaf litters of *Eucalyptus camaldulensis* on some forest and agricultural crops. J For Res 19(1):19–24

Ameen M (1999) Development of guiding principles for the prevention of impacts of alien species. Paper presented at a consultative workshop in advance of the 4th Meeting of SBSTTA to the CBD, organized by IUCN Bangladesh at Dhaka on 25 May 1999

Amin SMR, Ali MO, Fattah MIM. (eds.) (1995) Eucalypts in Bangladesh. Proceedings of a seminar held at the Bangladesh Agricultural Research Council, Dhaka on April 6, 1994. pp 73

Ashrafi Z, Mashhadi HR, Sadeghi S, Alizade HM (2008) Effects allelopathical of sunflower (*Helianthus annuus*) on germination and growth of wild varley (*Hordeum spontaneum*). J Agric Technol 4(1):219–229

Attiwill PM (1979) Nutrient cycling in a *Eucalyptus obliqua* (L'Herit.) forest. III. Growth, biomass, and net primary production. Aust J Bot 27(4):439–458

Ballester A, Vieitez AM, Vieitez E (1982) Allelopathic potential of Erica vegans, Calluna vulgaris and Daboecia cantabrica. J Chem Ecol 8:851–857

Bargali K, Bargali SS (2000a) Nutrient utilisation efficiencies of two central Himalayan tree species. J Trop For Sci 12(3):450–458

Bargali K, Bargali SS (2000b) Diversity and biomass of the understory vegetation in an age series of *Eucalyptus tereticornis* plantation. Int J Ecol Environ Sci 26:173–181

Bargali SS, Singh RP, Singh SP (1992a) Structure and function of an age series of eucalypt plantations in Central Himalaya, II. Nutrient dynamics. Ann Bot 69(5):413–421

Bargali SS, Singh SP, Singh RP (1992b) Structure and function of an age series of eucalypt plantations in Central Himalaya. I. Dry matter dynamics. Ann Bot 69(5):405–411

Bargali SS, Singh SP, Singh RP (1993) Patterns of weight loss and nutrient release from decomposing leaf litter in an age series of eucalypt plantations. Soil Biol Biochem 25:1731–1738

Bradstock R (1981) Biomass in an age series of *Eucalyptus grandis* plantations. Aust J For Res II:111–127

Catherine F, Benjamin L, Bruno V, Jean-Philippe M, Christine R, Stéphane G, Sylvie D, Anne BM (2006) Potential allelopathic effect of Pinus halepensis in the secondary succession: an experimental approach. Chemoecology 16:97–105

Catherine F, Sébastien V, Jean-Philippe M, Bruno V, Elena O, Sylvie D, Anne BM (2008) Regeneration failure of Pinus halepensis Mill: the role of autotoxicity and some abiotic environmental parameters. For Ecol Manag 255:2928–2936

Courtney KJ, Ward BB, Langenheim JH (1991) The effect of coastal redwood monoterpenes on *Nitrosomonas europaea*. Am J Bot 78:144–145

Davidson J (1985) Ecological and social aspects of eucalypts when used as exotics. In: J. Davidson and S. Das (eds.), *Eucalypts* in Bangladesh—a Review. Silviculture Bulletin No. 6. Chittagong. Bangladesh Forest Research Institute, pp 13–49

Davidson J, Das S (1985) *Eucalypts* in Bangladesh—A review. Bull. 6, Silv. Res. Div. Bangladesh Forest Research Institute, Chittagong, Bangladesh. Pp. 246

Del Fabbro C, Gusewell S, Prati D (2014) Allelopathic effects of three plant invaders on germination of native species: a field study. Biol Invasions 16:1035–1042

Djurdjević L, Popović Z, Mitrović M, Pavlović P, Jarić S, Oberan L, Gajić G (2008) Dynamics of bioavailable rhizosphere soil phenolics and photosynthesis of Arum maculatum L. in a lime—beech forest. Flora 203:590–601

Einhelling FA (1996) Interactions involving allelopathy in cropping systems. Agron J 88:886–893

Ens EJ, French K, Bremner JB (2009) Evidence for allelopathy as a mechanism of community composition change by an invasive exotic shrub, Chrysanthemoides monilifera spp. Rotundata. Pl Soil 316:125–137

Haque SMS (2013) Geology, soil science and forest soils. Degradation of upland watershed in Bangladesh project funded by USDA, Institute of Forestry and Environmental Science, p 332

Hasanuzzaman M, Hossain M, Saroar M (2004) Diversity and Preference of agricultural crops in the cropland agroforests of southwestern Bangladesh. Int J Agric Crop Sci 7(7):364–372

Hassan MM (1994) Prospects of Eucalypts in Bangladesh. Bangladesh J For Sci 23(1):12–19

Hong NH, Xuan TD, Eiji T, Khanh TD (2004) Paddy weed control by higher plants from Southeast Asia. Crop Prot 23:255–261

Hoque ATM, Ahmed R, Uddin MB, Hossain MK (2003a) Allelopathic effect of different concentration of water extracts of *Acacia auriculiformis* on some initial growth parameters of five common agricultural crops. Pak J Agron 2(22):92–100

Hoque ATMR, Uddin MB, Ahmed R, Hossain MK (2003b) Suppressive effects of aqueous extracts of *Azadirachta indica* leaf on some initial growth parameters of six common agricultural crops. Asian J Pl Sci 2(10):738–742

Hossain MK, Hoque ATMR (2013) *Eucalyptus* Dilemma in Bangladesh. Institute of Forestry and Environmental Sciences, University of Chittagong, Chittagong, p 148

Inderjit (2005) Soil microorganisms: an important determinant of allelopathic activity. Pl Soil 274:227–236

Jandová K, Dostá P, Cajtham T (2015) Searching for Heracleum mantegazzianum allelopathy in vitro and in a garden experiment. Biol Invasions 17:987–1003

Jones JM, Richards BN (1977) Effect of reforestation on turnover of ^{15}N labelled nitrate and ammonium in relation to changes in soil micro-flora. Soil Biol Biochem 9:383–392

Kaur H, Kaur R, Kaur S, Baldwin IT, Inderjit (2009) Taking ecological function seriously: soil microbial communities can obviate allelopathic effects of released metabolites. PLoS ONE 4:e4700

Keeley JE (1988) Allelopathy. Ecology 69:292–293

Khan MA, Khitran TA, Baloch MS, Suiemani MZ (1999) Allelopathic effect of eucalyptus on soil characteristics and growth of maize. Pak J Biol Sci 2(1):390–393

Lankau R (2010) Soil microbial communities alter allelopathic competition between Alliaria petiolata and a native species. Biol Invasions 12:2059–2068

May FE, Ash JE (1990) An assessment of the allelopathic potential of eucalyptus. Aust J Bot 38:245–254

Nektarios PA, Economou G, Avgoulas C (2005) Allelopathic effects of Pinus halepensis needles on turfgrasses and biosensor plants. HortScience 40(1):246–250

Nishimura H, Kaku K, Nakamura T, Fukazawa Y, Mizutani J (1982) Allelopathic Substances, (±)-p-Menthane-3,8-diols Iso- lated from *Eucalyptus citriodora* Hook. Agric Biol Chem 46:319–320

Powell KI, Chase JM, Knight TM (2013) Invasive plants have scale-dependent effects on diversity by altering species area relationships. Science 339:316–318

Reigosa MJ, Gonzalez L, Souto XC, Pastoriza JE (2000) Allelopathy in forest ecosystems. In: Tauro P (ed) Allelopathy in ecological agriculture and forestry. Kluwer, Dordrecht, pp 183–193

Rice EL (1984) Allelopathy, 2nd edn. Academic Press, Orlando, p 422

Shiva V, Bandyopadhyay J (1983) *Eucalyptus*—a disastrous tree in India. The Ecologist 13(5):184187

Si CC, Liu XY, Wang CY, Wang L, Dai ZC, Qi SS, Du DL (2013) Different degrees of plant invasion significantly affect the richness of the soil fungal community. PLoS ONE 8:e85490

Stowe LG (1979) Allelopathy and its influence on the distribution of plants in an Illinois old-field. J Ecol 67:1065–1085. doi:10.2307/2259228

Sun ZK, He WM (2010) Evidence for enhanced mutualism hypothesis: Solidago canadensis plants from regular soils perform better. PLoS ONE 5:e15418

Surendra MP, Pota KB (1978) On the allelopathic potentials of root exudates from different ages of *Celosia argenta* Linn. Natl Acad Sci Lett 1(2):56–58

Uddin MB, Ahmed R, Mukul SA, Hossain MK (2007) Inhibitory effects of *Albizia lebbeck* (L.) Benth. leaf extracts on germination and growth behavior of some popular agricultural crops. J For Res 18(2):128–132

Ward BB, Courtney KJ, Langenheim JH (1997) Inhibition of *Nitrosomonas europaea* by monoterpenes from coastal redwood (*Sequoia sempervirens*) in whole cell studies. J Chem Ecol 23(11):2583–2598

White CS (1986) Volatile and water—soluable inhibitors of nitrogen mineralization and nitrification in a ponderosa pine ecosystem. Biol Fertil Soils 2:97–104

White CS (1991) The role of monoterpenes in soil nitrogen cycling processes in ponderosa pine. Biogeochemistry 12:43–68

Wood SE (1996) Loss of foliar monoterpenes from *Umbellularia californica* leaf litter and their influence on nitrification potential in soil beneath the trees. PhD dissertation. University of California, Santa Cruz, p 151

Yang RY, Mei LX, Tang JJ, Chen X (2007) Allelopathic effects of invasive Solidago canadensis L. on germination and root growth of native Chinese plants. Allelopath J 19:241–248

Yuan YG, Wang B, Zhang SS, Tang JJ, Tu C, Hu SJ, Yong JWH, Chen X (2013) Enhanced allelopathy and competitive ability of invasive plant Solidago canadensis in its introduced range. J Pl Ecol 6:253–263

Zhang JH, Mao ZQ, Wang LQ, Shu HR (2007) Bioassay and identification of root exudates of three fruit tree species. J Integr Pl Biol 49:257–261

Zhang D, Zhang J, Yang W, Wu F (2010) Potential allelopathic effect of *Eucalyptus grandis* across a range of plantation ages. Ecol Res 25:13–23