2. Thrall, P. H., Hochberg, M. E., Burdon, J. J. and Bever, J. D., Coeolution of symbiotic mutualists and parasites in a community context. *Trends Ecol. Evol.*, 2007, **22**, 120–126.
3. Margulis, L. and Sagan, D., *Acquiring Genomes: A Theory of the Origin of Species*, Basic Books, New York, 2002.
4. Krajčovič, J., Ebringer, L. and Schwartzbach, S. D., Reversion of endosymbiosis? The case of bleaching in Euglena. In *Symbiosis: Mechanism and Model Systems* (ed. Seckbach, J.), Kluwer Academic, The Netherlands, pp. 185–206.
5. Kovačević, G., Value of the hydra model system for studying symbiosis. *Int. J. Dev. Biol.*, 2012, **56**, 627–635.
6. Arkhipchuk, W., Blaise, C. and Malinovskaya, M. V., Use of hydra for chronic toxicity assessment of waters intended for human consumption. *Environ. Pollut.*, 2005, **142**, 200–211.
7. Beach, M. J. and Pascoe, D., The role of *Hydra vulgaris* (Pallas) in assessing the toxicity of freshwater pollutants. *Water Res.*, 1998, **32**, 101–106.
8. Kalafatić, M. and Kopjar, N., Response of green hydra to pirimicarb. *Biol. Bratislava*, 1995, **50**, 289–292.
9. Satoh, A., Kurano, N., Harayama, S. and Miyachi, S., Effects of chloramphenicol on photosynthesis, protein profiles and transketolase activity under extremely high CO_2 concentration in an extremely-high-CO_2-tolerant green microalga, *Chlorococcumlittorale*. *Plant Cell Physiol.*, 2004, **45**, 1857–1862.
10. Wiedemann, B. and Heissig, P., Mechanisms of quinolone resistance. *Infection*, 1994, **2**, 73–79.
11. Chen, X., Ji, Z. L. and Chen, Y. Z., TTD: therapeutic target database. *Nucleic Acids. Res.*, 2002, **30**, 412–415.
12. Reynolds, E. S., The use of lead citrate at high pH as an electron opaque stain in electron microscopy. *J. Cell Biol.*, 1963, **17**, 208–212.
13. Kalafatić, M., Kovačević, G., Ljubešić, N. and Šunjić, H., Effects of ciprofloxacin on green hydra and endosymbiotic alga. *Period Biol.*, 2001, **103**, 267–272.
14. Kovačević, G., Kalafatić, M., Ljubešić, N. and Šunjić, H., The effect of chloramphenicol on the symbiosis between alga and hydra. *Biol. Bratislava*, 2002, **56**, 605–610.
15. Kovačević, G., Kalafatić, M. and Ljubešić, N., Endosymbiotic alga from green hydra under the influence of cinoxacin. *Folia Microbiol.*, 2005, **50**, 205–208.
16. Yellowlees, D., Rees, T. A. V. and Leggat, W., Metabolic interactions between algal symbionts and invertebrate hosts. *Plant Cell Environ.*, 2008, **31**, 679–694.
17. Puce, S., Bavestrello, G., Camillo, C. G. and Boero, F., Symbiotic relationships between hydroids and bryozoans. *Symbiosis*, 2007, **44**, 137–143.
18. Kovačević, G., Franjević, D., Jelenčić, B. and Kalafatić, M., Isolation and cultivation of endosymbiotic algae from green hydra and phylogenetic analysis of 18S rDNA sequences. *Folia Biol.* Kraków, 2010, **58**, 135–143.
19. Kovačević, G., Radić, S., Jelenčić, B., Kalafatić, M., Posilović, H. and Pevalek-Kozlina, B., Morphological features and isoenzyme characterization of endosymbiotic algae from green hydra. *Plant Syst. Evol.*, 2010, **284**, 33–39.
20. Kawaida, H., Ohba, K., Kontake, Y., Shimizu, H., Tachida, H. and Kabayakawa, Y., Symbiosis between hydra and Chrorella: molecular phylogenetic analysis and experimental study provide insight into its origin and evolution. *Mol. Phylogenet. Evol.*, 2013, **66**, 906–914.

ACKNOWLEDGEMENTS. We thank Nadica Vincek for technical support. This work was supported by the project 119-1193080-1214 of Croatian Ministry of Science, Education and Sport.

Received 9 November 2015; revised accepted 11 December 2015

doi: 10.18520/cs/v110/i6/1086-1088

Changes in the seasonal cycle of carbon stocks and fluxes due to fires in the grassland ecosystem of Manipur, Northeast India

A. Thokchom and P. S. Yadava*

Department of Life Sciences, Manipur University, Imphal 795 003, India

Fire is a common perturbation in the grassland ecosystems throughout the world. Effect of fire on carbon stock, rate of C-accumulation and soil CO_2 flux have been studied in *Imperata cylindrica–Sporobolus indicus*-dominated grassland community of Manipur, Northeast India. Carbon stock in the vegetation components was estimated to be 12.59 and 12.06 Mg ha^{-1} and soil organic carbon stock was found to be 57.28 and 44.74 Mg ha^{-1} in the control and burnt site respectively. It indicates that fire decreases the carbon stock in the grassland. However in the following year the annual rate of carbon accumulation increased in burnt site (7.94 Mg ha^{-1} year^{-1}) compared to the control site (6.75 Mg ha^{-1} year^{-1}) whereas the annual soil CO_2 flux decreased in the burnt site (4.06 Mg ha^{-1} year^{-1}) in comparison to the control site (7.26 Mg ha^{-1} year^{-1}). Our estimates of carbon budget reveal that the net uptake was 3.88 Mg C ha^{-1} year^{-1} in the grassland ecosystem after the burning treatment. Thus, the annual burning of grassland can cause major changes to carbon stocks and fluxes.

Keywords: Aboveground biomass, belowground biomass, carbon stock, carbon accumulation, soil CO_2 flux.

GRASSLANDS cover about one quarter of the earth's land surface[1] and span a range of climatic conditions from arid to humid. They play an important role in biosphere feedback of atmospheric CO_2 increase and climate change[2]. Grassland ecosystems can contribute to CO_2 mitigation through carbon accumulation in soil[3]. Grassland soils are high in soil organic carbon and contain an extensive fibrous root system, that creates an environment ideal for soil microbial activity[4]. Measurement of CO_2 flux from grassland soils supports their importance in global carbon budget[5].

Grasslands can vary greatly in their degree and intensity of management, from extensively managed rangelands to intensively managed. Anthropogenic land use is now widely considered to either contribute to carbon emissions through degrading land practices or to function as a carbon sink for atmospheric carbon through accumulation in below and aboveground forest and grassland components[6]. This has stimulated research on many different ecosystems regarding global carbon dynamics, and

*For correspondence. (e-mail: yadava.ps1@gmail.com)

their potential role in the recently developed carbon markets[7]. Reforestation and better grassland management are some of the ways through which carbon credits for the voluntary carbon market can be generated[8].

In many grasslands, the presence of fire is a key factor in preventing the invasion of woody species, which can significantly affect ecosystem carbon storage[9]. Fire is regarded as an active ecological agent able to mobilize nutrients and restore soil fertility[10], but it is also a primary cause of soil degradation due to nutrient loss for volatilization, leaching and erosion, especially in severe wild fires. It is, in fact, considered a major disturbance in many ecosystems leading to important shifts in soil properties and vegetation[11]. One of the most common effects of fire is the alteration in the composition and amount of soil organic matter[12]. Fire also influences the rate of soil CO_2 flux by changing the contribution of autotrophic respiration to total soil CO_2 flux and by modifying the amount of soil organic matter in the top soil.

Annual burning of grassland vegetation is a common practice not only in north eastern India but also in other parts of the world. It influences species composition and productivity and nutrient cycling in the grassland ecosystem. The Indian grasslands have originated from forest vegetation through deforestation and abandoned cultivation and are maintained at various succession levels owing to grazing and burning[13]. In north-eastern India, different grassland types occur owing to its origin from various forest types ranging from tropical rainforest, subtropical and temperate[14]. The effect of burning on vegetation carbon stock, soil organic carbon, soil CO_2 flux and greenhouse gas dynamics has been reported[15–18] by measuring the additional effect of fire management on aboveground and belowground C-dynamic. However limited information is available on effect of burning on carbon stock and accumulation in grassland ecosystems from north-eastern India. The main objectives of the present study were to assess the seasonal changes due to fires: (i) on carbon stock in vegetation and soil (ii) the rate of carbon accumulation and soil CO_2 flux in grassland ecosystem in Imphal, Northeast India. These objectives allowed us to test the hypothesis whether burning treatment increased or decreased C-accumulation in soil and vegetation and soil CO_2 flux in the grassland ecosystems.

The study site is located at 24°54′50.5″N and 94°06′16.8″E in Shabungkhok Khunou, around 20 km from Imphal city, in the Imphal East District of Manipur dominated by *Imperata cylindrica–Sporobolus indicus* grassland community. It was well protected during the study and burning treatment was performed in the part of the study area in February. The climate of the area is monsoonic with warm moist summers and cool dry winters. The year is divisible into three seasons, i.e. rainy (June–October), winter (November–February) and summer (March–May). The mean maximum temperature varied from 22.48°C (December) to 30.19°C (May) and the mean minimum temperature ranged from 4.97°C (January) to 22.94°C (August). Annual rainfall is 1166.80 mm and 65% of this fall in rainy season. The average relative humidity of air varied between 72.91% (March) and 85.97% (July).

Five permanent plots, each having an area of 10 m × 10 m, were selected randomly in the field in the control site. Areas adjacent to control plots were burnt completely on 1 February 2013, and from the burnt areas, a 10 m × 10 m size adjacent to each control plot was plotted and earmarked as burnt site. Biomass sampling was done from the last week of February 2013 and continued at a monthly interval until January 2014, comparing the control and burnt sites. Aboveground biomass was evaluated through harvest method by using 40 × 40 cm size of quadrates and belowground biomass was estimated from 15 × 15 × 30 cm soil monoliths in both the sites. These monoliths were soaked in water and the roots taken out separately. Harvested plant material was separated into live biomass, standing dead material, and litter and was dried in an oven at 80°C until constant weight.

Dried plant biomass was assumed to contain 50% carbon[19]. Soil organic carbon (SOC) was estimated[20], by taking the soil samples from different depths of 0–10, 10–20 and 20–30 cm. The SOC stock was estimated from bulk density, organic carbon concentration and the corresponding soil depths. The aboveground net production (ANP) and belowground net production (BNP) have been estimated by the summation of change in total shoot and root biomass in different months throughout the year, following the method given by Singh and Yadava[21]. Total net production (TNP) is the summation of ANP and BNP, and multiplied by 50% of carbon concentration to determine C-accumulation in ANP, BNP and total C-accumulation.

Soil CO_2 flux was measured on a monthly basis from February 2013 to January 2014, in both the study sites through the Soil Respiration System (Q-BOX SR1LP), Canada. Statistical analysis was carried out using the software IBM SPSS 20 and Statistica. ANOVA was used to determine the difference in various months of the year. Simple linear regression was used to find out the relationship between soil carbon stock and litter biomass. *t*-tests were used to compare the biomass and soil CO_2 flux in the two sites.

Live aboveground biomass ranged from 108.33 ± 54.1 gm^{-2} (February) to 411.39 ± 64.8 gm^{-2} (September) in control site (Figure 1 *a*) and 20.25 ± 7.4 gm^{-2} (February) to 448.44 ± 91.4 gm^{-2} (October) in burnt site in different months throughout the year (Figure 1 *b*). Average mean monthly aboveground biomass was higher in the control than that of burnt site.

Maximum aboveground biomass was recorded in September in the control site and October in the burnt site. It is obvious as most of the annual species and aerial parts of perennial species attained maturity by September/

October, and start drying up more rapidly due to onset of cold and dry period. Aboveground biomass was significantly different between the two study sites ($t = 3.73$; $df = 12$; $P = 0.001$).

The vegetation of burnt site prolongs the grand growth period by sprouting their shoots earlier and delaying in maturity of the species in addition to their high biomass accumulation. Therefore annual burning of grassland during later part of winter season (January/February), seems to be an appropriate technique for the removal of standing dead and litter, in enhancing sprouting of new shoots; and delay in maturity of the species and thus increase in the productivity of humid grasslands.

The analysis of variance shows a significant difference in aboveground biomass between the samples collected in different months in the control ($F = 35.43$; $df = 11$; $P < 0.001$) and burnt site ($F = 35.46$; $df = 11$; $P < 0.001$).

In the control site, the amount of standing dead material was between 316.25–500.3 gm^{-2} and 44.71–385.43 gm^{-2} in burnt site (Figure 1). The maximum value of standing dead was recorded in December/January in both sites due to transfer of live biomass to standing dead during cool and dry winter months.

In the control site, litter varied from 50.50 ± 16.1 gm^{-2} (April) to 74.81 ± 24.7 gm^{-2} (January; Figure 1 *a*). The maximum value in January might be due to larger transfer of standing dead materials to litter and slow decomposition of litter in cool and dry period. In the burnt site, litter was recorded only from August (18.6 ± gm^{-2}) due to burning in February, and increased consistently attaining a maximum value of 27.05 ± 7.2 gm^{-2} in October (Figure 1 *b*). The analysis of variance shows a significant difference between the litter samples collected in different months in both the sites ($F = 2.26$; $df = 11$; $P < 0.01$).

In the control site, belowground biomass ranged from 1581.0 ± 530.1 gm^{-2} (May) to 2303.2 ± 240.9 gm^{-2} (January; Figure 2). The minimum value in May may be due to upward translocation of assimilates from the roots that are used to support the growth of sprouts after monsoon shower and the maximum value during winter months is due to downward translocation of food reserve to roots and rhizome due to drying up of aerial parts of plants[21]. Thus, the cool and dry period is congenial, for the build-up of higher biomass in belowground parts in the grasslands. Similar trend was also observed in burnt site with a minimum in May (1601.9 ± 128.9 gm^{-2}) and maximum in January (2251.6 ± 463.6 gm^{-2}) though the average value of belowground biomass was slightly higher than that of control site. No significant difference was observed in the belowground biomass in the control and burnt site ($t = 1.83$; $df = 12$; $P > 0.001$). It shows that fire has not impacted the belowground biomass in the present grassland.

Our data of carbon stock in total aboveground biomass showed higher values (3.28 Mg C ha^{-1}) in control site than that of burnt site (1.99 Mg C ha^{-1}). In both the sites the carbon stock in total aboveground biomass was highest in rainy season and lowest in summer season (Table 1). Out of the total aboveground biomass, 33% and 52% was reflected in live biomass in control and burnt site respectively, and rest stored in dead stand and litter. Higher storage of C in live biomass in burnt site may be due to the fertilizing action of the ash material on the soil surface and increased the fertility of the soil. Our data of carbon stock in aboveground biomass in control site was similar to the data reported in tropical alpine tussock

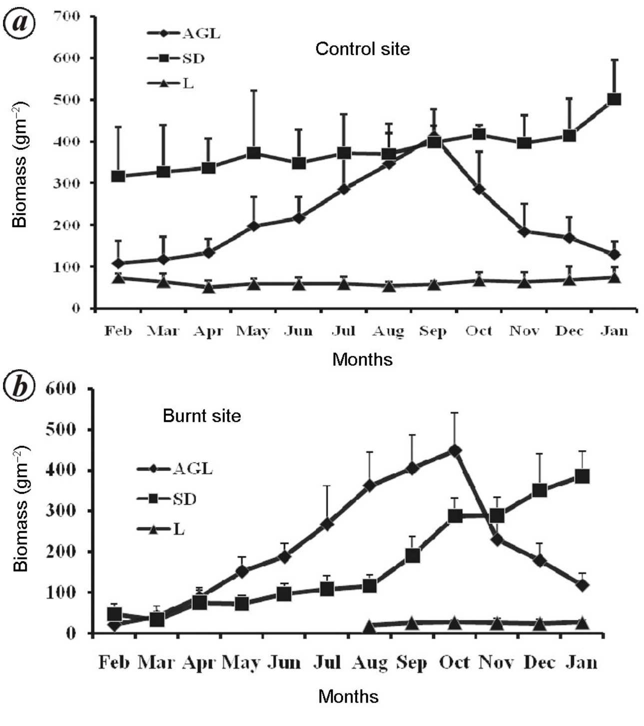

Figure 1. Monthly variation in the aboveground live biomass (AGL), standing dead (SD) and litter (L) biomass in the (***a***) control and (***b***) burnt site ecosystem (gm^{-2}).

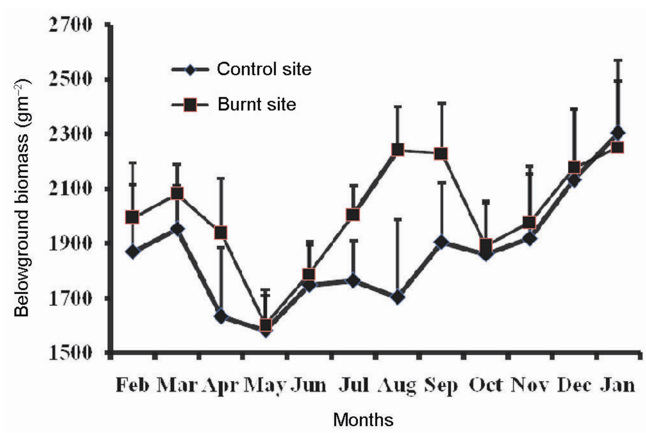

Figure 2. Monthly variation in the belowground biomass in the control and burnt site in the ecosystem of Manipur, North East India (gm^{-2}).

Table 1. Mean annual carbon stock in aboveground live, standing dead, litter, total aboveground, belowground and soil organic carbon stock in the control (C) and burnt site (B) grassland ecosystem of Manipur, North East India (Mg ha^{-1})

	Summer season		Rainy season		Winter season		Annual	
Components	C	B	C	B	C	B	C	B
Aboveground live	0.75	0.46	1.55	1.67	0.74	0.68	1.07	1.03
Standing dead	1.72	0.29	1.90	0.79	2.03	1.34	1.90	0.84
Litter	0.29	0.00	0.29	0.12	0.35	0.13	0.31	0.12
Total aboveground	2.76	0.76	3.74	2.43	3.12	2.11	3.28	1.90
Belowground	8.60	9.36	8.98	10.15	10.28	10.50	9.31	10.07
Soil organic carbon stock	56.00	42.19	64.98	49.24	48.63	41.03	57.28	44.73

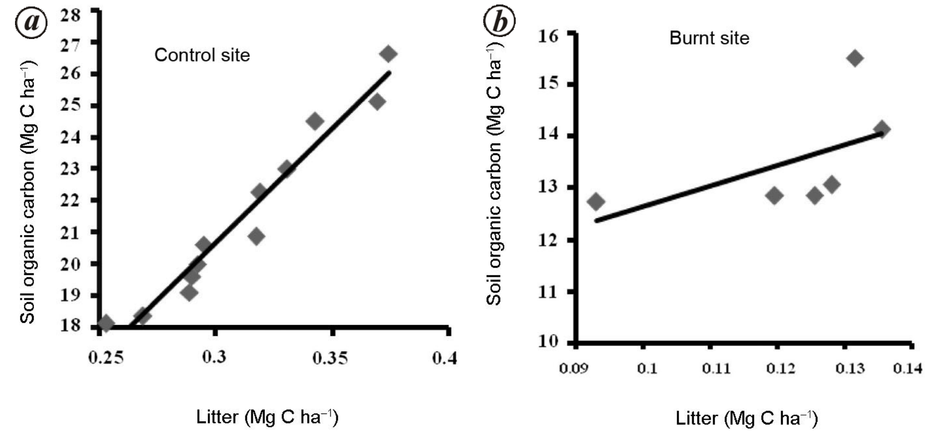

Figure 3. Relationship between soil organic carbon stock and carbon stock in the litter biomass in the (***a***) control and (***b***) burnt site.

grasslands[22], but less than that in the grazed grassland of Peru[21] (6.5 Mg ha^{-1}) and in Ecuadorian paramo grassland (4.0 to 4.2 Mg ha^{-1})[23].

Carbon stock in belowground biomass was highest in winter season followed by rainy and summer season (Table 1). The present study shows higher values for *Leymus chinensis* grassland of Northern China[24] (5.57 Mg ha^{-1}) and Brazilian Cerrado wet grass[25] (2.58 to 2.77 Mg ha^{-1}). Thus it shows that the tropical grassland has high capacity in storing of carbon in belowground than the temperate grasslands. Out of total carbon in biomass (AGB + BGB) 73.8% and 88.6% of carbon was stored in belowground biomass of control and burnt site respectively, and was similar to the finding reported in the grassland of China[26], where 88.1% of carbon is stored in belowground biomass. It shows that high percentage carbon stock in the belowground parts is an adaptive feature of the grasslands.

The SOC was higher (57.28 ± 11.23 Mg ha^{-1}) in control than burnt site (44.74 ± 12.3 Mg ha^{-1}). In both the sites SOC stock was highest in rainy season and lowest in winter season (Table 1) because of faster decomposition of plant debris during the winter season.

The high value of soil carbon stock in the control site is due to high rate of litter production and faster decomposition of litter. The SOC stock in the soil was related with the litter as given by the linear regression equation, $y = 72.02x - 0.911$ in the control site and $y = 39.78x + 8.657$ in the burnt site, where y = soil organic carbon (Mg C ha^{-1}) and x = C stock in litter biomass (Mg C ha^{-1}). This relation shows a significant positive correlation in both the sites; $r = 0.98$; $P < 0.001$, Figure 3 *a* in the control and $r = 0.55$; $P < 0.001$, Figure 3 *b* in the burnt site. It explains 95% and 30% variability in the SOC stock in the control and burnt sites respectively due to variability in the carbon stock of litter biomass. Thus it shows that litter components have been the controlling factors in the storage of carbon in the soil. The soil organic carbon stock was higher in the control site than the burnt site as fire consumed litter in the beginning of study and similar finding was also reported in the semi-arid grasslands[17].

The present data on SOC stock in the control site (57.28 Mg ha^{-1}) is comparable to the data reported in Pasture, Australia[27] (50–164 Mg ha^{-1}) and in semi-natural grassland in Southern China[28] (28.1–417 Mg ha^{-1}) but greater than the burnt site in the present grassland ecosystem.

Out of the total organic carbon in soil and vegetation system, 79–82% was stored in soil and 18–21% in the

Table 2. Seasonal and mean annual rate of carbon accumulation in the aboveground, belowground and total rate of accumulation in the control (C) and burnt site (B) in grassland ecosystem (Mg C ha^{-1})

	Summer season		Rainy season		Winter season		Annual	
Components	C	B	C	B	C	B	C	B
Aboveground carbon accumulation	0.64	0.78	1.22	2.90	0.31	0.04	2.17	3.53
Belowground carbon accumulation	0.46	0.43	1.91	2.19	2.22	1.79	4.55	4.41
Total carbon accumulation	1.06	1.21	3.13	5.09	2.53	1.83	6.72	7.94

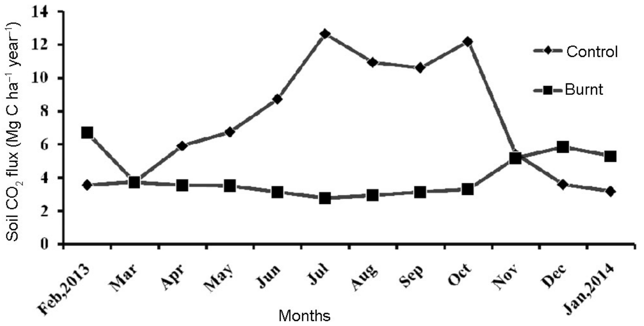

Figure 4. Soil CO_2 flux (Mg C ha^{-1} $year^{-1}$) in different months in the control and burnt site.

vegetation in both the sites. Thus the present study reveals that most of the carbon in the studied grassland is stored in soils than that of the vegetation components, where C turnover times of the bulk soil carbon are relatively long.

The annual rate of aboveground C accumulation was higher in burnt site (3.53 Mg C ha^{-1} $year^{-1}$) than the control site (2.17 Mg C ha^{-1} $year^{-1}$) (Table 2). It seems fire promotes luxuriant growth of grasses on the addition of nutrients from the ash content by enhancing soil fertility. The new shoots sprouted from the rhizomes shortly after the fire, which was due to the removal of the apical dominance by killing the old shoots by fire and reserve mobilization[29]. The increased of rate of accumulation in the burnt site may also be due to the removal of the shading effect and the exponential growth of younger tillers was an additional factor, stimulating shoot production in burnt site and the availability of more nutrient from the burnt ash materials.

The rate of belowground ground C accumulation was found to be 4.55 and 4.41 Mg C ha^{-1} $year^{-1}$ in the control and burnt site respectively (Table 2). It is similar in both the sites during the summer season but during the rainy season burnt site had higher rate of accumulation. Perhaps the luxuriant growth of the annual plants, contributes to more root production in the burnt site due to addition of more nutrients on burning in the preceding season.

In the present grassland the rate of carbon accumulation in belowground was higher than that of aboveground parts in both burnt and control grassland. It shows that belowground parts play a significant role in C accumulation. Sims and Singh[30] described that photosynthates are translocated downwards, to storage regions in the roots and thus help increase the productivity of belowground parts.

In the present study we find that the total rate of carbon accumulation (AGB + BGB) was higher in the burnt site than the control site, in the *Imperata cylindrica–Sporobolus indicus* grassland community and was in the order of rainy > winter > summer season in both the sites. Thus annual burning of grassland during dry winter season seems to be unique technique, for the removal of standing dead shoot and accumulated litter, in enhancing new shoot sprouting and delay in maturity of the species, which results in the enhancement of accumulation of carbon.

Soil CO_2 flux ranges from 3.16 to 12.64 Mg C ha^{-1} $year^{-1}$ in the control site and 2.52 to 6.69 Mg C ha^{-1} $year^{-1}$ in the burnt site (Figure 4). The average annual soil CO_2 flux was higher in control site (7.26 ± 3.44 Mg C ha^{-1} $year^{-1}$) than that of burnt site (4.06 ± 1.33 Mg C ha^{-1} $year^{-1}$). These results indicate that fire had a transient effect on the rate of soil CO_2 flux. Burnt plot emitted significantly less soil CO_2 than the control site. In control site all C in the organic matter is returned to the atmosphere via decomposition pathways. However in burnt plots, fire removes organic carbon in grassy fuels and leaf litter, before it has a chance to enter decomposition pathways, reducing belowground inputs. These estimates suggest that the removal of the litter layer by fire in the previous dry season results in the decrease of the rate of soil CO_2 flux, and influences soil C cycling by altering the plant-derived organic matter. A decrease in the rate of soil respiration in the burned grassland than the control of west Ethiopia is also reported[19].

Our present study shows that the rate of soil CO_2 flux was lower than that reported on tropical savannas[21] (17.8 Mg C ha^{-1} $year^{-1}$ in the control site and 7.7 Mg C ha^{-1} $year^{-1}$ in the burnt site), but greater than that of the grassland of central Africa[18] (4.49 Mg C ha^{-1} $year^{-1}$ in the control site and 3.22 Mg C ha^{-1} $year^{-1}$ in the burnt site). The difference is probably due to difference in methodology and the frequency of fire.

We also find a significant seasonal changes in the rate of soil CO_2 flux due to burning treatment. In the control site, the rate of soil CO_2 flux was higher in the wet season

Table 3. Annual C-budget in control and burnt site of the grassland ecosystem of Manipur, North East India.

Components	Control	Burnt
C-stock in aboveground vegetation (Mg ha^{-1})	1.07	1.03
C-stock in standing dead and litter (Mg ha^{-1})	2.21	0.96
C-stock in roots (Mg ha^{-1})	9.31	10.07
Total C-stock in vegetation (Mg ha^{-1})	12.59	12.06
C-stock in soil up to depth of 30 cm (Mg ha^{-1})	57.28	44.74
Soil CO_2 flux (Mg C ha^{-1} $year^{-1}$)	7.26	4.06
Rate of carbon accumulation (Mg C ha^{-1} $year^{-1}$)	6.72	7.94
Net carbon balance (Mg C ha^{-1} $year^{-1}$)	–0.54	3.88

(11.01 Mg C ha^{-1} $year^{-1}$) than the dry season (4.58 Mg C ha^{-1} $year^{-1}$) which was reversed in the case of the burnt site, where lower rate of soil CO_2 flux was recorded in the wet season (3.41 Mg C ha^{-1} $year^{-1}$) than the dry season (4.52 Mg C ha^{-1} $year^{-1}$) due to low input on burning of litter in later part of winter season and low microbial activity. We find that the rate of soil CO_2 flux was more than three-fold higher on control plots compared to the burnt plots in the wet season. Not much difference was observed between control and burnt site in the dry season ($t = 0.07$; $df = 12$; $P > 0.01$), because of the senescence of the grass layer and also of the decrease of soil moisture, which lessen the diffusion of organic C-substrate through the soil profile and lower the microbial activity. In the burnt site, there was low rate of soil CO_2 flux in the wet season and similar observations were also reported on the burned grassland of Ethiopia[19] and on the tropical savannas of Australia[21].

Annual carbon pool and carbon flux rate in the different components of grassland ecosystem are shown in Table 3. Carbon stock in aboveground parts was comparatively higher in control site than burnt site, but it was reversed in belowground parts as it exhibited higher in the burnt site. The soil carbon stock and rate of soil CO_2 flux were higher in control site than those of burned site due to heavy load of standing dead transfer to litter during summer, coupled with congenial environmental conditions and high microbial activity during wet season. Rate of C-accumulation was higher in burnt site than that of control in the year following fire. Our estimates of carbon budget reveal that an accumulation of 3.88 Mg C ha^{-1} $year^{-1}$ was found in the grassland ecosystem on fire treatment and maintained normal equilibrium in control site.

In conclusion, the present study indicates that burning has a dramatic effect on the carbon stock and soil CO_2 flux in the sub-tropical grassland ecosystem dominated by *Imperata cylindrica–Sporobolous indicus*. The difference in the rate of carbon accumulation and soil CO_2 flux in the control and burnt site indicates that burning has a significant effect on the grassland ecosystem. Thus the present study reveals that burning enhances the rate of accumulation in the year following fire by prolonging the grand growth period of the vegetation by sprouting their shoots earlier and delaying in maturation of grasses. However the soil carbon stock and soil CO_2 flux decline on burning because of combustion of surface litter inputs and the decrease in the root activity and exhibited strong seasonality. Thus the sensitivity of the rate of C-accumulation and soil CO_2 flux to different land use practices (fire and grazing) suggest that it is critical to include these factors in the development of grassland C-budgets and C-cycling in the formulation of the regional models.

1. Ojima, D. S., Parton, W. J., Schimel, D. S., Scurlock, J. M. O. and Kittel, T. G. F., Modeling the effects of climatic and CO_2 changes on grassland storage of soil C. *Water, Air Soil Pollut.*, 1993, **70**, 643–657.
2. Hall, D. O., Ojima, D. S., Paton, W. J. and Scurlock, J. M. O., Response of temperate and tropical grassland to CO_2 and climate change. *J. Biogeo.*, 1995, **22**, 537–547.
3. Bronson, K. F., Zobeck, T. M., Chua, T. T., Acosta-Martinez, V., Van Pelt, R. S. and Booke, J. D., Cabon and nitrogen pools of southern high plains cropland and grassland soils. *J. Am. Sci. Soc.*, 2004, **68**, 1695–1704.
4. Conant, R. T., Dalla-Betta, P., Klopatek, C. C. and Klopatek, J. M., Controls on soil respiration in semiarid soils. *Soil Biol. Biochem.*, 2004, **36**, 945–951.
5. Mielnick, P. C. and Dugas, W. A., Soil CO_2 flux in a tall grass praire. *Soil Biol. Biochem.*, 2000, **32**, 221–228.
6. Denman, K. L. *et al.*, Couplings between changes in the climate system and biogeochemistry. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Solomon, S. *et al.*), Cambridge University Press, Cambridge, 2007.
7. Glenday, J., Carbon storage and emissions offset potential in an east African tropical rainforest. *For. Ecol. Manage.*, 2006, **235**, 72–83.
8. Hamilton, E. W., Frank, D. A., Hinchey, P. M. and Murray, T. R., Defoliation induces root exudation and triggers positive rhizospheric feedbacks in a temperate grassland. *Soil Biol. Biochem.*, 2008, **40**, 2865–2873.
9. Jackson, R. B., Banner, J. L., Jobbágy, E. G., Pockman, W. T. and Wall, D. H., Ecosystem carbon loss with woody plant invasion of grasslands. *Nature*, 2002, **418**, 623–626.
10. Snyman, H. A., Short-term response of rangeland following an unplanned fire in terms of soil characteristics in a semi-arid climate of South Africa. *J. Arid. Environ.*, 2003, **55**, 160–180.
11. Certini, G., Effects of fire on properties of forest soils: a review. *Oecologia*, 2005, **143**, 1–10.
12. Knicker, H., How does fire affect the nature and stability of soil organic nitrogen and carbon? *Biogeochemistry*, 2007, **85**, 91–118.

13. Yadava, P. S., Savannas of North East India. *J. Biogeogr.*, 1990, **17**, 385–394.
14. Champion, H. G. and Seth, S. K., *A Revised Survey of the Forest Ecosystems of India*, Manager Publication, Govt of India, New Delhi, 1968.
15. Castaldi, S., Grandcourt, A., Rasile, A., Skiba, U. and Valentini R., CO_2, CH_4 and N_2O fluxes from soil of a burned grassland in Central Africa. *Biogeoscience*, 2010, **7**, 3459–3471.
16. Michelson, A., Anderson, M., Jensen, M., Kjøler, A. and Gashew, M., Carbon stocks, soil respiration and microbial biomass in fire-prone tropical grassland, woodland and forest ecosystem. *Soil Biol. Biochem.*, 2004, **36**, 1707–1714.
17. Novara, A., Gristina, L., Rühl, J., Pasta, S., Angelo, G. D., Mantia, T. L. and Pereira, P., Grassland fire effect on soil organic carbon reservoirs in a semiarid environment. *Solid Earth*, 2013, **4**, 381–385.
18. Richards, A. E., Dathe, J. and Cook, G. D., Fire interacts with season to influence soil respiration in tropical savannas. *Soil Biol. Biochem.*, 2012, **53**, 90–98.
19. Gibbon, A. *et al.*, Ecosystem carbon storage across the grassland forest transition in the high Andes of Manu National Park, Peru. *Ecosystems*, 2010, **13**, 1097–1111; doi: 10.1007/s10021-010-9376-8.
20. Anderson, J. M. and Ingram, J. S. I., *Tropical Soil Biology and Fertility Programme, TSBF Methods Handbook*, International Union of Biological Sciences, 1993, p. 77.
21. Singh, J. S. and Yadava, P. S., Seasonal variation in composition, plant biomass and net primary productivity of a tropical grassland at Kurukshetra. *Ecol. Monogr.*, 1974, **44**, 351–378.
22. Oliveras, I. *et al.*, Grass allometry and estimation of aboveground biomass in tropical alpine tussock grasslands. *Austr. Ecol.*, 2013, **39**, 408–415; doi: 10,1111/acc.12098.
23. Ramsay, P. M. and Oxley, E. R. B., An assessment of aboveground net primary productivity in Andean grasslands of Central Ecudor. *Mountain Res. Dev.*, 2001, **21**, 161–167.
24. He, N., Yu, Q., Wu, L., Wang, Y. and Han, X., Carbon and nitrogen store and storage potential as affected by land use in a *Leymus chinensis* grassland of Northern China. *Soil Biol. Biochem.*, 2008, **40**, 2952–2959.
25. Fidelis, A., Lyra, M. F. S. and Pivello, V. R., Above and belowground biomass and carbon dynamics in Brazilian Cerrado Wet grassland. *J. Veg. Sci.*, 2013, **24**, 356–364.
26. Fan, J. *et al.,* Carbon storage in the grasslands of China based on field measurements of aboveground and belowground biomass. *Climate Change*, 2008, **86**, 375–396; doi: 10.1007/s 10584-007-9316-6.
27. Chan, K. Y. and McCoy, D., Soil carbon storage potential under perennial pastures in the mid-north coast of New South Wales Australia. *Trop. Grassland*, 2010, **44**, 184–191.
28. Toma, Y. *et al.*, Soil carbon stocks and carbon sequestration rates in semi-natural grassland in Aso region, Kumamoto, Southern Japan. *Global Change Biol.*, 2013, **19**, 1676–1687.
29. Pandey, A. N., Short term study of recovery of tropical grassland following seasonal burning. *Trop. Ecol.*, 1988, **29**, 159–170.
30. Sims, P. L. and Singh, J. S., The structure and function of ten Western Northern America grasslands. III. Net primary production, turnover and efficiency of energy capture and water use. *J. Ecol.*, 1978, **66**, 573–597.

ACKNOWLEDGEMENTS. We thank CSIR, New Delhi for providing financial support under a research project. We are grateful to Prof. J. Srinivasan, IISc, Bengaluru for his critical review and valuable suggestion on the manuscript.

Received 8 October 2015; revised accepted 22 November 2015

doi: 10.18520/cs/v110/i6/1088-1094

Development of ductile shear zones during diapiric magmatism of nepheline syenite and exhumation of granulites – examples from central Rajasthan, India

A. B. Roy[1,*], Krishan Dutt[2] and Sanjeeb Rathore[3]

[1]Department of Geology, Presidency University, Kolkata 700 073, India
[2]H. No. 20/75, Mansarovar, Jaipur 302 020, India
[3]No. 301, A.R. Complex, I-Block, Sector-14, Hiran Magri, Udaipur 313 001, India

The present communication discusses two separate instances where features commonly observed in DSZ are noted, one along the margin of the Kisengarh nepheline syenite and the other in the granulite bodies in the Sandmata Complex in Rajasthan, India. The foliations in the nepheline syenite pluton show features similar to the mylonite gneisses that characterize DSZs in orogenic belts. Apart from simulating LS tectonite-type fabric, the continuity of similar structures in adjacent cover rocks provides evidence of heterogeneous deformation during upward ascent of nepheline syenite. Based on tectono-metamorphic studies on granulites suggestion is made about the uplift of deep-seated granulites accompanied by ductile shearing along the margins. The development of DSZ along margins helped in reducing frictional resistance during upward ascent and emplacement into Archaean gneissic terrane. The process is comparable to buoyancy-induced diapiric uplift of hot plutonic bodies through cooler upper crust.

Keywords: Ductile shear zone, diapiric magmatism, exhumation of granulites, emplacement of plutonic bodies.

THE term 'mylonite' as defined by early workers implied grain size reduction by brittle processes[1–3]. This continued to be the common perception until lately with the result that more importance was given to the microtextural study in understanding the tectonic history and nature of deformation in the shear-zone rocks[4,5]. In the present-day usage, mylonites are considered to be intensely deformed rocks produced predominantly by ductile flow[6]. Evidence of strong crystal-plastic deformation in the mylonites helps to separate these rocks from the cataclastic rocks formed during brittle deformation[7].

The zones of mylonites showing presence of a penetrative foliation, marked by a strong stretching-type lineation are often interpreted as exhumed 'fossil' ductile shear zones (DSZs)[8,9]. Compared to the gneissic foliation that develops in the zones of low strain (Figure 1 *a*), the mylonite foliation in a DSZ appears more regular and

*For correspondence. (e-mail: ashitbaranroy@gmail.com)