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Effect of Precipitation and Nitrogen Input on Soil Respiration in Grasslands

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Abstract

Nowadays soil respiration has become an important issue in research. Measurement of soil respiration helps in determining the carbon budget under the influence of global climate change. Rainfall variability and nitrogen (N) input both have a profound impact on soil respiration and its components, i.e. autotrophic and heterotrophic respiration. Besides, soil respiration also shows considerable change due to global warming. According to emissions scenario, the elevated CO_2 concentration would increase the soil surface temperature by 2°C in the coming 35 years which may lead to huge C-losses to the atmosphere. Such carbon losses to the atmosphere would aggravate the effects of global warming on the human race. Although some progress had been made in soil respiration research about rainfall variability and N-input, there are discrepancies in the results. But despite considerable scientific attention in recent years, there is no consensus on the direction and magnitude of warming-induced changes in soil carbon. Soil respiration changes with climate but to confirm it observationally have big constraints such as high spatial variability in soil respiration, inaccessibility of the soil medium and inability of the instruments to measure soil respiration on large scales. Further, most of the soil respiration studies about rainfall variability and N-input have been conducted in temperate regions, and tropics have remained ignored. Though tropical countries have not yet experienced the extreme variations in rainfall, still under the ongoing climate change the tropical region would also start to experience altered rainfall regimes. Rainfall variability and N-input are the consequences of intense global climate change and industrialisation, respectively. There are reports from grasslands that the antecedent soil moisture determines the strength of the effect of rainfall on soil respiration. N-input is reported to increase soil respiration only when water addition accompanied it. Further, the effect of N-input on soil respiration was different for the short term and long term addition of nitrogen. Likewise many ecosystem warming experiments suggest that warming increases the carbon fluxes to and from the soil, but the net global balance between these responses is uncertain.

1. Introduction

Model predictions and observations have indicated changes in rainfall regimes in the tropics (Greve *et al*., 2014; Chadwick *et al*., 2015). These changes in rainfall lead to an intensification of hydrological cycle that may comprise change in magnitude, frequency and seasonality of rainfall (Huntington, 2006). Precipitation changes are spatially heterogeneous and less predictable than the other drivers of major climate change (Beier *et al*., 2012) and these may lead to incidences of intense flooding as well as long-term drought periods. Such incidences in addition to the increased CO_2 concentration in the atmosphere and increased temperature, modify the soil water availability (Daly and Porporato, 2005). Changing precipitation regimes govern soil water availability (Gupta and Singh, 1981) affecting such ecosystem processes as soil respiration (Liu *et al*., 2009). Soil respiration is a phenomenon of returning photosynthetically fixed CO_2 to the atmosphere (Högberg and Read, 2006). On an average, 68 to 80 Pg (petagrams, 1 Pg=10^{15} g) of CO_2 is released to the atmosphere per year (Raich and Schlesinger, 1992) which is ten times more than the CO_2 released during fossil fuel burning (Schlesinger, 1997). But as of now global soil respiration over the entire earth's land surface was 98±12 Pg C in the year 2008 which has increased by 0.1 Pg C yr^{-1} between 1989 and 2008 (Bond-Lamberty and Thomson, 2010). This dataset apparently shows that soil respiration do change by a factor of 1.5 for every 10°C increase in temperature (Bond-Lamberty and Thomson, 2010). Thus it is evident that rising temperatures will cause a net loss of soil carbon to the atmosphere, developing a positive land carbon-climate feedback that could enhance the climate change.

Soil respiration is governed by a number of abiotic and biotic factors such as soil temperature, soil moisture, atmospheric CO_2, substrate quality and availability, microbial community structure, vegetation and land use and the variety of extant disturbance regimes (Davidson and Janssens, 2006). Another factor which has been little focused but has a profound consequence is the nitrogen (N) deposition and its effect on carbon cycling and storage. Gruber and Galloway (2008) have reported that reactive nitrogen-input has approximately doubled after industrialisation. According to Bai *et al*. (2010), fossil fuel combustion, use of fertiliser, land use change have caused great changes to ecosystem structure and functions and so has nitrogen deposition (Galloway *et al*., 2004). So far no consistent result has been obtained for the response of soil respiration to N-addition in different ecosystems and regions (Lee and Jose, 2003; Xu and Wan, 2008; Janssens *et al*., 2010), primarily due to varied conditions of soil temperature and moisture (Zhang *et al*., 2017). N-addition affects both biotic and abiotic drivers of soil respiration, i.e. above and below ground plant biomass and its ratio (Cleveland and Townsend, 2006), microbial biomass (Allison *et al*., 2008), litter quality and quantity (Knorr *et al*., 2005), soil moisture (Xu and Wan, 2008) and temperature (Zhang *et al*., 2014). Studies suggest that N-addition, when coupled with increased precipitation in dryland areas, lead to increased belowground productivity resulting in more C supply, therefore more soil respiration (Yan *et al*., 2010). Hence, by evaluating the belowground plant biomass, we can understand atleast partially the mechanism underlying the response of soil respiration to nitrogen addition.

Here, we want to speculate how precipitation variability, nitrogen deposition, elevated atmospheric CO_2 concentrations and global warming would altogether affect the phenomenon of soil respiration.

2. Soil Respiration in Grasslands

Grasslands cover approximately 40% of the total land area on earth excluding the area under permanent ice-cover (White *et al*., 2000) and hence they have a significant role in the global carbon cycle. Soil respiration is one of the major pathways for emitting back CO_2 to the atmosphere (Bond-Lamberty and Thomson, 2010) and thus plays an important role in maintaining global carbon cycling (Davidson and Janssens, 2006; Phillips *et al*., 2012). Among the abiotic factors, soil temperature and soil water availability have major effects on soil respiration (Verhoef *et al*., 1996). Changes in both of these factors are the direct consequence of global warming and altered precipitation regimes. The variation in the response of soil respiration to temperature increase is due to its interaction with soil water availability (Wang *et al*., 2014). Soil respiration is composed of two components- autotrophic respiration from roots and heterotrophic respiration from soil microbes and fauna. The combination of autotrophic and heterotrophic respiration poses a great challenge in evaluating soil respiration and its role in global carbon cycling (Jassal and Black, 2006; Hinko-Najera *et al*., 2015). Autotrophic respiration depends upon the assimilation of photosynthates in the belowground plant parts for root activity (Högberg *et al*., 2001; Shi *et al*., 2011) while heterotrophic respiration depends upon the microbial activity during decomposition of SOC (Hanson *et al*., 2000; Hinko-Najera *et al*., 2015). These two components under the influence of changing environmental factors including temperature and soil water availability have a strong impact on the soil C-storage (Boone *et al*., 1998; Luan *et al*., 2011). Soil CO_2 flux reflects the large pool of mineralizable C in soil as heterotrophic respiration which is one of the major components of soil respiration along with autotrophic respiration (Wiant, 1967; Ryan and Law, 2005). Thus the efflux of CO_2 from the mineralizable C pool in the soil increases with environmental changes and exhibits a positive response to the global warming by increasing the atmospheric CO_2 concentration (Rustad *et al*., 2000). Many times the contribution of root respiration makes the role of soil respiration unclear in the context of global warming (Kuzyakov, 2002a,b; Cheng *et al*., 2005).

Soil respiration from grasslands is an important determining factor for the estimation of global terrestrial soil respiration because they make the most widespread vegetation type throughout the entire globe. Table 1 represents the area of total grassland distributed between the temperate and tropical regimes and their respective contribution to the annual soil CO_2 efflux and the share of root respiration. Contribution from temperate countries to soil respiration from meadow steppes, prairies are enormous but tropical grasslands have remained neglected, and studies are needed to predict the role of these grasslands as a carbon source or sink in the future.

3. Soil Respiration in Response to Precipitation Variability and N-Input

In dry ecosystems, water and soil nutrient

Table 1: Annual soil CO_2 efflux, % contribution of root respiration to total soil respiration from temperate and tropical grasslands (Based on Wang and Fang, 2009).

Grassland type	Area occupied (million km^2)	Annual soil CO_2 efflux (Pg C yr^{-1})	% contribution of root respiration to total soil respiration
Temperate grasslands	9	3.51	32
Tropical grasslands	15	9.02	54

availability are considered as the important limiting factors in determining the primary productivity of the ecosystem and mineralization of soil organic matter as soil moisture and soil nutrient availability regulate the supply of C-substrates to plant roots and soil microbes (Illeris *et al*., 2003; Ouyang *et al*., 2008). Change in the timing and amount of rainfall in dry ecosystems under the influence of global climate change will have undoubtedly impacts on carbon balance in the ecosystem. Fierer and Schimel (2003) reported a 500% increase in soil respiration measured in dry condition followed by wetting in grasslands. On the other hand, Bouma and Bryla (2000) reported a decrease in soil respiration after a heavy rainfall event due to less or no diffusion of CO_2 from the soil due to water-filled pore spaces of fine-textured soil.

In addition to precipitation variability, if the concentration of nitrogen in the atmosphere continues to increase, the global N-deposition would almost get doubled in the coming 25 years (Moore *et al*., 2009). Increasing population and its huge demand for food results in the massive application of nitrogenous fertilisers, leading to nitrogen deposition (Erisman *et al*., 2008). Studies by Craine *et al*. (2001), Xu and Wan (2008) showed that N-input increased soil respiration while other studies have shown no effect or negative effect of N-input on soil respiration (Raich and Tulekcioglu, 2000; Micks *et al*., 2004). Recent studies report that effect of N-addition on soil respiration varies with the amount of N added (Gao *et al*., 2014) and soil N content of the soil (Janssens *et al*., 2010).

As per the findings of Hanson *et al*. (2000), Schlesinger and Andrews (2000) soil carbon dioxide (CO_2) efflux (i.e. soil respiration) accounts for 70-90% of total ecosystem respiration thereby becoming the largest source of CO_2 from terrestrial ecosystems. So the response of soil respiration to precipitation and N-addition is crucial under the climate change entailing increased frequency of drought periods and precipitation amount (Dore, 2005).

4. Effect of Water Addition on Soil Respiration and its Components (Simulating Precipitation)

In the time to come, many regions on the globe would exhibit higher mean annual temperature and intra-annual variability in precipitation events. Global circulation models project a 0.7% increase in global mean precipitation for this century, more particularly in tropics and at middle and high latitudes (Solomon *et al*., 2007). With increases in precipitation amount, the intensity of precipitation events and frequency of extreme events are also projected to increase (Easterling *et al*., 2000). Seasonality may also change exhibiting summer with fewer rainfall events and winters with more rainfall events (Kalvova and Nemešová, 1997). Soil respiration, an ecosystem process depends upon the sporadic rainfall events. Therefore it is most sensitive to the predicted precipitation regimes (Huxman *et al*., 2004). A study by Matías *et al*. (2011) concludes that in the time to come, precipitation variability will play a more important role in the regulation of soil respiration rather than temperature. The study also inferred that temperature regulates soil respiration only when soil moisture is not a limiting factor. Increased precipitation variability accounts for the change in soil water content and soil temperature which in turn influences the root growth and biological activity in soil (Gupta and Singh, 1981). Thus the increased precipitation variability either increases (Sponseller, 2007) or decreases the soil respiration (Davidson *et al*., 2000). Figure 1 represents the relationship of soil respiration to changed precipitation amount, size and seasonality (Shen *et al*., 2008). Large precipitation events lead to two contradictory results; one is the increase in soil water content which in turn increases soil CO_2 efflux from soil (Davidson *et al*., 2000). The second most likely outcome of large precipitation event is decreased in soil respiration after heavy precipitation event due to

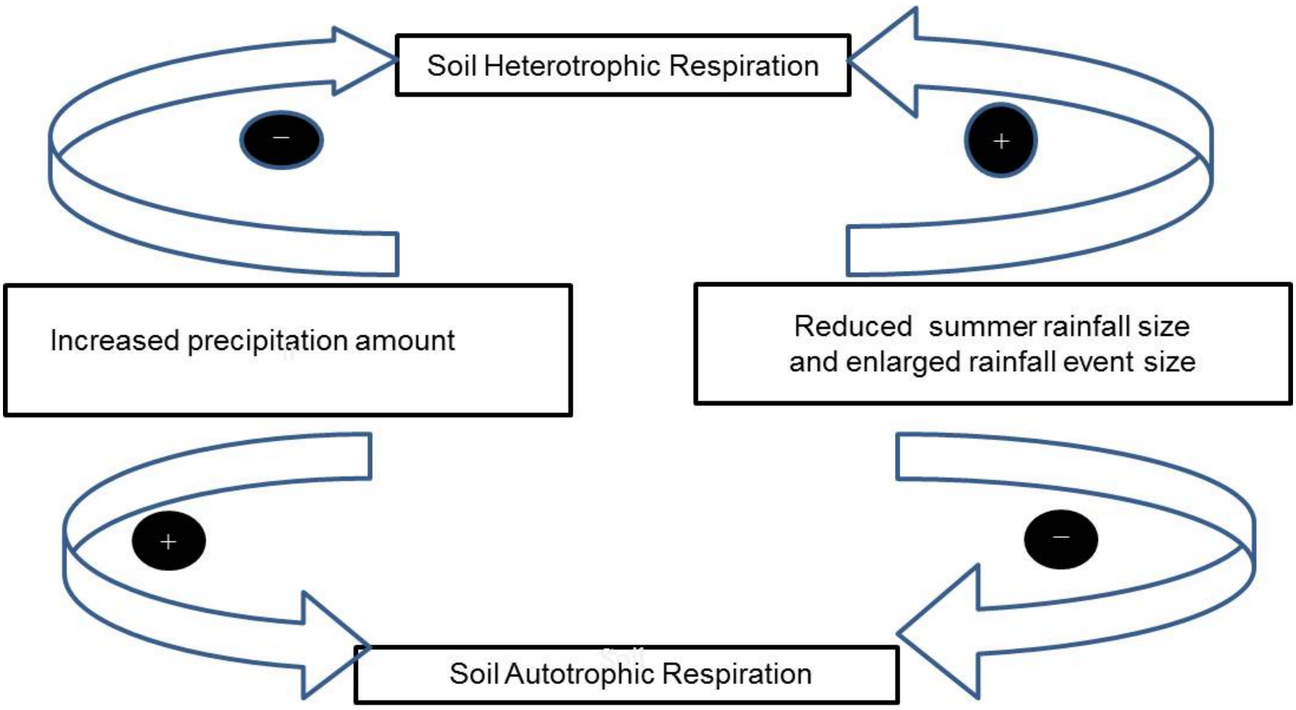

Fig. 1: Effect of change in precipitation amount, size and seasonality on soil respiration. In the bottom panel, '+' indicates the increase in soil autotrophic respiration with increased precipitation amount and '−' indicates the decrease in soil autotrophic respiration with reduced summer rainfall size and enlarged rainfall event size. In the top panel '+' indicates the increase in soil heterotrophic respiration with reduced summer rainfall size and enlarged rainfall event size and '−' indicates the decrease in soil heterotrophic respiration with increased precipitation amount (Based on Shen *et al.*, 2008).

blockage in the diffusivity of CO_2 through the water-filled pore spaces in the soil. Many studies showed that rainfall events generate short-term pulses in grassland soils (Fay *et al.*, 2002; Knapp *et al.*, 2002; Xu and Baldocchi, 2004). Study in mid-latitude forests also showed that soil respiration pulses induced by rainfall account for 5-10% of annual net ecosystem production (Lee *et al.*, 2004) and 90% of late season ecosystem respiration in semi-arid grasslands (Xu and Baldocchi, 2004). Thus it is the rainfall-induced fluxes which determine whether an ecosystem acts as a source or sink of atmospheric CO_2 (Shim *et al.*, 2009).

Rainfall, in general, affects soil respiration and hence its components autotrophic respiration (SR_a) and heterotrophic respiration (SR_h). A survey of literatures depicted that experiments simulating precipitation by addition of water in different amounts and frequency, significantly increase soil respiration components i.e. SR_a (autotrophic respiration) and SR_h (heterotrophic respiration) (Mariko *et al.*, 2007; Patrick *et al.*, 2007) thereby increasing total soil respiration ($SR_{tot} = SR_a + SR_h$). Water addition stimulates plant growth, thus increasing the supply of carbon to the roots, hence increasing SR_a (Högberg *et al.*, 2001; Shi *et al.*, 2011). Water addition also increases SR_h but not to the extent of SR_a. Increase in SR_h was on account of the increase in microbial activity and biomass (Fierer *et al.*, 2003). Increase in both SR_a and SR_h was greater when the antecedent soil moisture was low because it is the antecedent soil moisture which determines microbial biomass activity (Vangestel *et al.*, 1991), plant growth and photosynthesis (Liang *et al.*, 2002; Potts *et al.*, 2006) and diffusivity of CO_2 through soil profile (Davidson and Janssens, 2006).

5. N-Input as Determinant of Soil Respiration

Studies unfold the fact that N-addition stimulates both above and below ground net primary productivity by virtue of which the SR_a increases while the increase in SR_h is not much affected because N-addition in low amounts does not affect microbial activity and biomass (Liu *et al.*, 2007). Studies also showed that both low and high dose of N-addition has a different effect on soil respiration and belowground plant biomass by affecting plant and microbe's N demands Figure 2. To

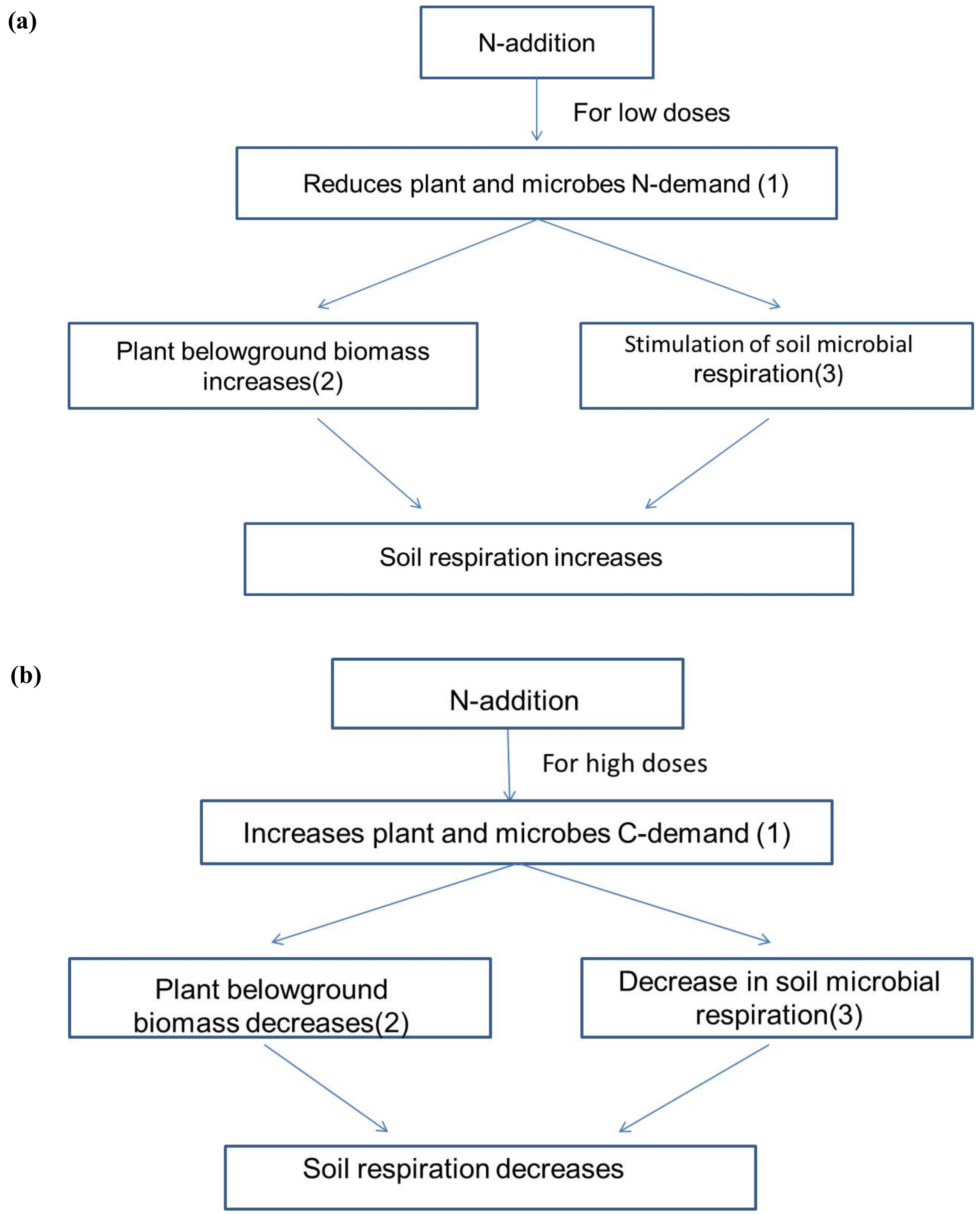

Fig. 2: (a) Representing the effect of N-addition on soil respiration (for low doses). Number in each box represents the source 1 = Xia and Wan, 2008; 2 = Micks *et al.,* 2004; 3 = Wei *et al.* 2013. (b) Representing the effect of N-addition on soil respiration (for high doses). 1 = Aber *et al.,* 1989; 2 = Giardina *et al.*, 2004; 3 = Bowden *et al.*, 2004.

assess the effect of nutrient availability on soil respiration, alpine grasslands being rich in soil organic carbon content, extensive root biomass and low nutrient availability, are the best to study (Ren *et al*., 2016).

In a study at alpine grassland in the Qinghai-Tibetan Plateau, in China, N-addition (100 kg ha^{-1} $year^{-1}$) for four years, i.e. from 2009-2012, gave inconsistent results. During the first year of the experiment, N-addition stimulated soil respiration rate in the growing season because when the nitrogen was added in the first year, it stimulated the plant growth, microbial activity and plant biomass (Micks *et al*., 2004). In the next two years, N-addition did not affect soil respiration while in the fourth year soil respiration rate decreased. This varied response of soil respiration in alpine grassland to N-addition is on account of the temporal differences in the responses of microbial activity to N-addition. The down-regulation of SR_a is due to increased N-availability (Zhou *et al*., 2014). The fact behind the reduction in SR_h upon addition of a significant amount of nitrogen is N-toxicity (osmotic potential or pH) and decreasing availability of C which dwindles the microbial population (Treseder, 2008). Thus such responses of soil respiration to increased nutrient availability show that these grassland ecosystems could function as a carbon sink.

6. Effect of Water and N-Input on the Components of Soil Respiration

It is a well-known fact that the two basic abiotic factors in controlling the process of soil respiration are soil temperature and soil moisture. Soil water availability most probably determines the effect of temperature on soil respiration (Conant *et al*., 2004). Previous studies put forth the fact that N is a major limiting factor in grasslands, as N-addition stimulated plant growth. But here also, the results of N-addition are not consistent. In areas where N is a limiting factor, N-addition increases soil respiration while in areas which are not N-limited, N-addition exhibits the opposite effect (Janssens *et al*., 2010). Studies done in North and Central American grasslands showed that root biomass increases with N-availability (Tilman and Wedin, 1991), while studies from alpine meadows in India yield opposite result, here the root biomass decreased after two years of N-application (Ram *et al*., 1991). Thus we are compelled to believe that a range of factors, including N- and water content is responsible for the growth of belowground vegetation biomass. In a study in arid/semiarid grasslands of Inner Mongolia, China, it was observed that precipitation played an important role in the temporal and spatial distribution of N-deposition (Li *et al.*, 2015). Bai *et al*. (2010) performed a four-year experiment with different levels of N-application and found that above ground net primary-productivity remained unaffected by N-addition under dry conditions. The same increased 4-times the mean value recorded for that region on over 105 kg N ha^{-1} application under relatively moist conditions. The grassland was much more sensitive to N-induced changes as a result of higher soil moisture increasing the N-limitation.

It has been reported that the increased N-input slows down the soil organic matter mineralisation and reduces soil respiration (Bowden *et al*., 2004). N-addition increases plant growth which in turn increases the CO_2 uptake (Templer *et al*., 2012). On the other hand, the reason behind reduced soil respiration on N-deposition is due to a combined decrease in root respiration on N-availability and reduction in microbial demand for N-containing organic matter of recalcitrant types (Ambus and Robertson, 2006).

7. Effect of Warming and Elevated Atmospheric CO_2 on Soil Respiration

Soil respiration exhibits a positive exponential correlation with temperature. Thus global warming would stimulate soil respiration and will develop a positive feedback loop between atmospheric CO_2 and air temperatures (Cox *et al*., 2000). The movement of carbon (C) between soil and atmosphere show a prominent control on atmospheric C concentrations and the climate change (Mahecha *et al*., 2010) because soil respiration being a biological process is driven by plant, microbes and animals that live in soil and whose activities get altered by anthropogenic warming. Despite the growing confidence that warming increases carbon flux to and from the soil (Arora *et al*., 2013), the net global carbon balance between these responses is still uncertain.

In a study by Wan *et al*. (2007), the responses of soil respiration to air warming depended not only on CO_2 concentration but also on the season and soil water availability. Seasonal variation in soil respiration responses to warming is due to presence or absence of soil moisture (Janssens and Pilegaard, 2003). In a study by Crowther *et al*. (2016), conducted at 49 experimental fields across North America, Europe and Asia, upon the effect of warming on soil carbon stocks, infers that the result of warming depends on the size of initial carbon stock with substantial losses taking place in high-latitude areas. On account of the high sensitivity of C-decomposition to high temperature large soil C stocks are more vulnerable to warming-induced losses. Thus, increased C-decomposition outpaces C-accumulation from enhanced plant growth causing considerable C-losses to the atmosphere. While in ecosystems with minor soil C-stock, warming-induced accelerated decomposition causing negligible C losses which get compensated by concurrent increases in plant growth and soil C-stabilization (Macias-Fauria *et al*., 2012). The study also extrapolates that 1°C of warming over 35 years will lead to the loss of 203±161 Pg C from the upper soil horizon (Crowther *et al*., 2016). If this C, as expected, entered the atmosphere would increase the atmospheric load of CO_2 by approximately 25 parts per million. Thus having profound effects on plant production (Rustad *et al*., 2001), belowground carbon allocation which in turn influences root and microbial respiration both positively and negatively. Hence, elevated CO_2, air warming in interaction with changing precipitation have complex effects on soil respiration.

8. Recommendations and Future Prospective

Till date, it is not very clear as to how precipitation treatments including precipitation amounts, seasonality and intensity individually and in combination affect soil respiration. So we still need to research in the direction of estimating soil respiration under different precipitation regimes. Besides, it is also found that N-addition gives a greater stimulation to soil respiration and its components during the wet season compared to the dry season (Jia *et al*., 2012). It has been inferred that response of soil respiration to soil moisture is non-linear in general (Deng *et al*., 2011). Though we have now begun to generate a global picture of the temperature sensitivity of soil respiration (Mahecha *et al*., 2010) and total soil C stocks but still our understanding about the warming influences on global soil C inputs is limited (Koven *et al*., 2015).

Our future recommendations would include precise partitioning of components of soil respiration, to accurately predict their differential responses under the future global climate change. We also need to carry out long-term researches on the response of SR, SR_a, and SR_h to nitrogen addition for precise quantification of soil respiration and subsequent carbon sequestration. Under the climate change scenario, we also need to study soil respiration responses to precipitation, nitrogen deposition and global warming to have more information about the interacting effects of these global change drivers on soil C-dynamics. The influence of global warming on soil respiration cannot be overlooked because rising temperatures stimulate the loss of soil C to the atmosphere which could enhance the planetary warming over the 21st century (Jenkinson *et al*., 1991).

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