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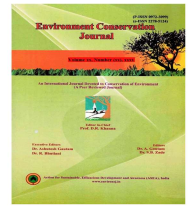

Sulphur Dynamics under different land uses of Outer Himalayan region of Himachal Pradesh

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ABSTRACT

The knowledge of different sulphur (S) forms and their relationship with soil properties is of much relevance in assessing the short- and long-term availability of the nutrients to crops and in formulating sound fertilizer recommendations. For this purpose one hundred and one representative soil samples were collected from the study area and analyzed for various physicochemical properties and forms of sulphur (water soluble, exchangeable, available, organic, non-sulphate and total S) using standard methods. The different forms of sulphur viz., water soluble, exchangeable, available, organic, non-sulphate and total sulphur ranged from 1.1 to 7.0, 1.9 to 10.9, 3.1 to 21.1, 75.9 to 316.1, 8.0 to 41.5 and 75.5 to 372.5 mg kg^{-1}, respectively in soils of Outer Himalayas under different land uses. The content of different forms of sulphur present in these soils were in the order of total sulphur, organic sulphur, non-sulphate sulphur, available sulphur, exchangeable sulphur and water soluble sulphur. All the forms of S correlated positively and significantly with organic carbon and clay content of soils. A negative and significant relationship was also observed between all forms of sulphur and sand content of soils. In the present study, it was also found that all forms of S present in soils were significantly and positively correlated with each other. The knowledge regarding different forms of S in soils and their availability controlled by different soil properties will be helpful for its management to optimize crop yields in the Outer Himalayas of Himachal Pradesh.

Introduction

Sulphur is one of the 17 mineral nutrients which are essential for the growth and development of plants. Sulphur is also essential for human and animals and is increasingly being recognized as the fourth major plant nutrient after nitrogen, phosphorus and potassium. Sulphate sulphur is the most abundant form of inorganic sulphur found in most of the soils and it is the form that the plants generally take up, although other reduced forms, such as elemental sulphur, thiosulphate and sulphide are important for anaerobic soils (Zhou *et al.,* 2005). However, the bulk of soil sulphur in natural and managed ecosystems is in organic form, which is directly affected by microbial activity through decomposition processes (Solomon *et al.,* 2001). The occurrence of sulphur deficiencies in Indian

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soils has increased manifolds with increasing use of high analysis fertilizers with low sulphur content, and greater crop removal of the nutrient from the ever increasing multiple cropping systems. Based on the recent Indian Council of Agricultural Research (ICAR) report, out of total soil samples analyzed across 20 states, on an average 33 percent of samples were deficient in sulphur. Sulphur exists in different forms, the knowledge of these forms of sulphur in soils together with their distribution in the root zone is of much relevance in assessing the sulphur supplying capacity of the soils (Azmi *et al.,* 2018). The nature and amount of various forms of sulphur depends on variation in soil texture, pH, calcium carbonate, organic matter and many other soil physical and chemical characteristics (Zho Hua-Yun *et al.,* 2015). The availability of sulphur in a soil is not only influenced by management practices but also depends upon various forms of sulphur present as these different forms of sulphur exist in dynamic equilibrium in soil (Azmi *et al.,* 2018). Major agricultural land of Outer Himalayas is under maize-wheat sequence, paddy-wheat sequence, vegetable based cropping sequences, sugarcane based cropping sequences and orchards. These crops are cultivated without addition of sulphur fertilizers. Since no systematic information is available regarding distribution of sulphur forms in these agriculturally important soils of the Outer Himalayas of Himachal Pradesh, the present study was undertaken to assess the status of different forms of sulphur and delineate the area of deficiency or sufficiency of sulphur.

Material and Methods

Description of study area

Himachal Pradesh is situated between 30°23′40″N to 33°12′40″ N latitudes and 75°45′55″ E to 79°04′20″ E longitudes with an area of 55, 673 sq km. The Outer Himalayas of Himachal Pradesh (popularly known as the *shivalik* hills) covers an area of 9.13 lakh ha at an altitude ranging from 350 to 650 m above mean sea level in Una, Bilaspur, Hamirpur, Sirmaur, Kangra and Solan districts of Himachal Pradesh. Five land uses were chosen for this study and these were Maize-Wheat, Paddy-Wheat, vegetable based cropping sequences, sugarcane based cropping sequences and orchard belonging to the soil orders *Inceptisol* and *Entisol*. The annual rainfall of the area is around 1100 mm and the prevailing temperature lies between 15 °C to 23 °C.

Location and procedure of soil sampling

A total of 101 soil samples were collected from the cultivated areas of Una, Bilaspur, Hamirpur, Sirmaur, Kangra and Solan districts of Himachal Pradesh (Figure 1). Out of these one hundred and one sites 38, 15, 18, 15 and 15 sites represent the soils under maize-wheat, paddy-wheat, vegetables, sugarcane and fruit trees, respectively. Land use sites for taking soil samples were selected on the basis of cropping pattern followed and cultivation history. Representative sampling sites were selected randomly from each land use. Three representative units were selected from each land use and from each unit composite soil samples were collected from ten soil subsamples (points). Soil samples from 0 to 15 cm and 15 to 30 cm depth for the agricultural lands under field crops and established orchards/ plantations, respectively were collected randomly using stainless steel soil augers and taken to the laboratory for analysis. The latitude, longitude and mean sea level of the sampling sites were recorded using a handheld global positioning system. Collected soil samples were air dried, ground to pass a 2-mm sieve after stone and debris were removed, and then stored in plastic bottles for analysis in laboratory

Soil analysis

The processed soil samples were analyzed for important soil properties *viz.,* pH, electrical conductivity (EC), organic carbon (OC), mechanical separates, cation exchange capacity (CEC), base saturation (BS) & calcium carbonate content ($CaCO_3$) and available nutrient status using standard methods (Piper 1966; Jackson 1977). Total and organic-S were determined as per methods outlined by Chapman and Pratt 1961 arid Bradsley and Lancaster (1965), respectively. Available S was extracted with 0.15% $CaCl_2$ (Williams and Steinbergs 1959). Sulphur in all the extracts was determined by the turbidimetric procedure of Chesnin and Yien (1951). The difference between organic S plus available S contents and total S was denoted as non-sulphate S.

Results and Discussion

Physicochemical properties

The results showed that sand (%), silt (%), clay (%), textural class, soil pH (1:2.5), EC (µS cm^{-1}), OC (g kg^{-1}), CEC {cmol(p+) kg^{-1}}, BS (%) and $CaCO_3$ (%) in these soils varied from 40 to 80, 12

Table 1: Physical and chemical properties of soils under different land uses.

Cropping sequence	Soil texture				pH (1:2.5)	EC (µS cm^{-1})	OC (g kg^{-1})	CEC {cmol (p^+)kg^-}	BS (%)	$CaCO_3$ (%)
	Sand (%)	Silt (%)	Clay (%)	Class						
Maize-wheat	40-79 (58)	12-45 (27)	6-24 (14)	sl-scl	6.1-7.3 (6.8)	153-270 (187)	3.1-15.3 (6.6)	4.9-13.3 (8.1)	60-76 (68)	0.05-0.45 (0.24)
Paddy-wheat	47-66 (57)	23-25 (29)	10-18 (14)	sl-l	6.5-7.6 (7.0)	143-287 (208)	3.8-9.9 (7.4)	6.1-10.4 (8.0)	62-77 (69)	0.40-1.95 (0.95)
Vegetable based cropping sequences	47-80 (61)	12-35 (26)	7-21 (13)	ls-scl	6.1-7.6 (7.0)	145-372 (240)	3.6-11.7 (6.9)	4.8-11.2 (7.6)	61-74 (68)	0.28-1.30 (0.60)
Sugarcane based cropping sequences	53-74 (62)	19-32 (25)	7-15 (13)	sl	6.7-7.8 (7.2)	175-318 (232)	4.5-9.1 (6.2)	4.8-8.0 (6.9)	67-75 (71)	1.00-2.20 (1.84)
Orchards	40-76 (59)	15-36 (27)	7-24 (14)	sl-l	6.3-7.3 (6.9)	142-229 (181)	3.7-9.9 (6.4)	4.7-12.6 (7.6)	61-76 (68)	0.20-0.30 (0.24)

Note: sl=sandy loam, l=loam, ls=loamy sand, scl=sandy clay loam
Values in parenparenthesis "()" indicates mean

Table 2: Distribution of S fractions in soils under different land uses

Cropping Sequence	Sulphur forms					
	WS-S	Ex-S	Av-S	Org-S	NS-S	Total-S
	(mg kg^{-1})					
Maize-wheat	1.1-7.0 (3.5)	1.9-10.9 (5.9)	3.1-17.9 (9.4)	75.9-316.1 (143.4)	8.0-40.5 (22.6)	92.3-372.5 (175.4)
Paddy-wheat	1.8-5.8 (4.1)	2.7-10.3 (6.8)	4.5-16.0 (10.9)	99.5-204.3 (157.3)	17.2-29.0 (21.5)	122.4-247.2 (189.4)
Vegetable based cropping sequence	1.5-6.3 (3.9)	2.5-10.4 (6.4)	4.0-16.5 (10.8)	81.6-240.5 (147.1)	9.5-35.5 (20.3)	96.5-281.9 (177.7)
Sugarcane based cropping sequence	2.5-5.7 (3.5)	4.6-8.6 (5.8)	7.1-14.3 (9.3)	93.0-177.7 (130.9)	9.2-25.0 (19.6)	110.2-215.0 (159.9)
Orchards	1.7-5.7 (3.5)	2.7-9.0 (5.7)	4.5-14.7 (9.2)	84.5-208.7 (137.7)	9.8-41.5 (23.1)	106.0-255.3 (170)

Note: WS=Water soluble, Ex=Exchangeable, Av=Available, Org=Organic, NS=Non sulphate
Values in parenparenthesis "()" indicates mean

to 45, 6 to 24, loamy sand to sandy clay loam, 6.1 to 7.8 (slightly acidic to slightly alkaline), 142 to 372, 3.1 to 15.3, 4.7 to 13.3, 60 to 77 and 0.05 to 2.20 with respective mean values of 59, 27, 14, 7.0, 205, 6.7, 7.8, 69 and 0.70 in cultivated soils of Outer Himalayas of Himachal Pradesh region (Table 1).

Distribution of sulphur forms

Water soluble sulphur

The water soluble sulphur content in these soils ranged from 1.1 to 7.0 mg kg^{-1} with mean value of 3.7 mg kg^{-1}. On an average, it constituted 1.99, 2.16, 2.19, 2.19 and 2.06 per cent of total S in soils under maize-wheat sequence, paddy-wheat sequence, vegetable based cropping sequences, sugarcane based cropping sequences and orchards, respectively (Figure 2). Water soluble S exhibited a significant positive correlation with organic carbon (r=0.80*), CEC (r=0.71*) and clay (r=0.74*) and significant negative with sand (r=-0.22*) (Table 3). The amount of water soluble sulphur in soils of the study area is comparable with that reported by Bandyopadhyay and Chattopadhyay (2001) and Majumdar and Patil (2017).

Exchangeable sulphur

Exchangeable sulphur in these soils ranged from 1.9 to 10.9 mg kg^{-1} with mean value of 6.1 mg kg^{-1}. On an average, it constituted 3.36, 3.59, 3.60, 3.63 and 3.35 per cent of total S in soils under maize-wheat sequence, paddy-wheat sequence, vegetable based cropping sequences, sugarcane based cropping sequences and orchards, respectively

Table 3: Simple correlation coefficients between sulphur forms and soil properties.

Sulphur Forms	Soil properties								
	Sand	Silt	Clay	pH	EC	OC	CEC	BS	$CaCO_3$
WS-S	-0.22*	0.18	0.74*	-0.10	-0.10	0.80*	0.71*	-0.14	-0.26
Ex-S	-0.21*	0.19	0.84*	-0.18	-0.12	0.84*	0.70*	-0.15	-0.28
Av-S	-0.22*	0.19	0.80*	-0.08	-0.10	0.80*	0.70*	-0.11	-0.27
Org-S	-0.21*	0.17	0.68*	-0.15	-0.14	0.79*	0.68*	-0.16	-0.28
NS-S	-0.24*	0.17	0.72*	-0.12	-0.05	0.46*	0.58*	-0.05	-0.19
Total-S	-0.25*	0.19	0.64*	-0.09	0.02	0.80*	0.68*	-0.08	-0.18

***Significant at 5 per cent level of significance**
Note: WS=Water soluble, Ex=Exchangeable, Av=Available, Org=Organic, NS=Non sulphate

Table 4: Simple correlation coefficients between Sulphur forms

S Forms	WS-S	Ex-S	Av-S	Org-S	NS-S	Total-S
WS-S	-					
Ex-S	0.78*	-				
Av-S	0.76*	0.78*	-			
Org-S	0.61*	0.62*	0.59*	-		
NS-S	0.51*	0.51*	0.55*	0.48*	-	
Total-S	0.55*	0.59*	0.60*	0.81*	0.49*	-

***Significant at 5 per cent level of significance**
Note: WS=Water soluble, Ex=Exchangeable, Av=Available, Org=Organic, NS=Non sulphate

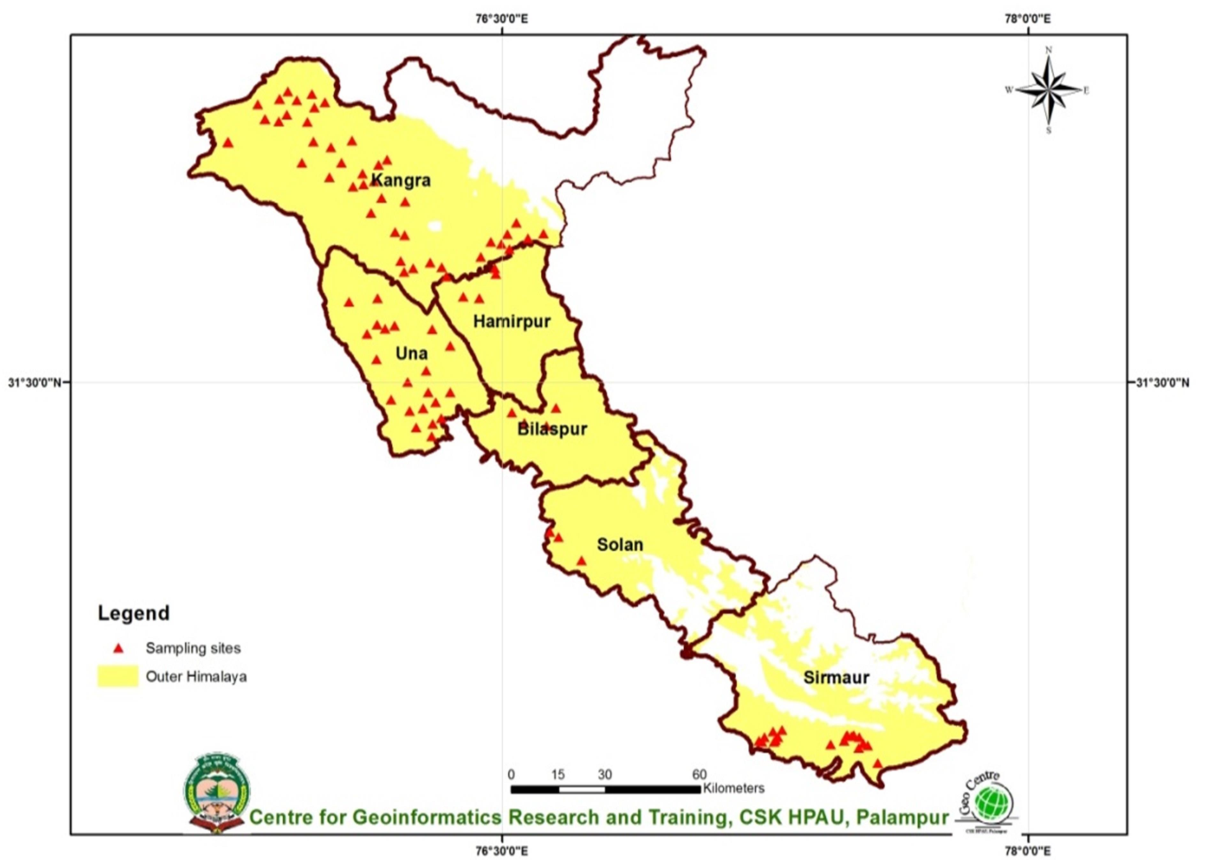

Figure 1: Location of soil sampling sites in Outer Himalayan region of Himachal.

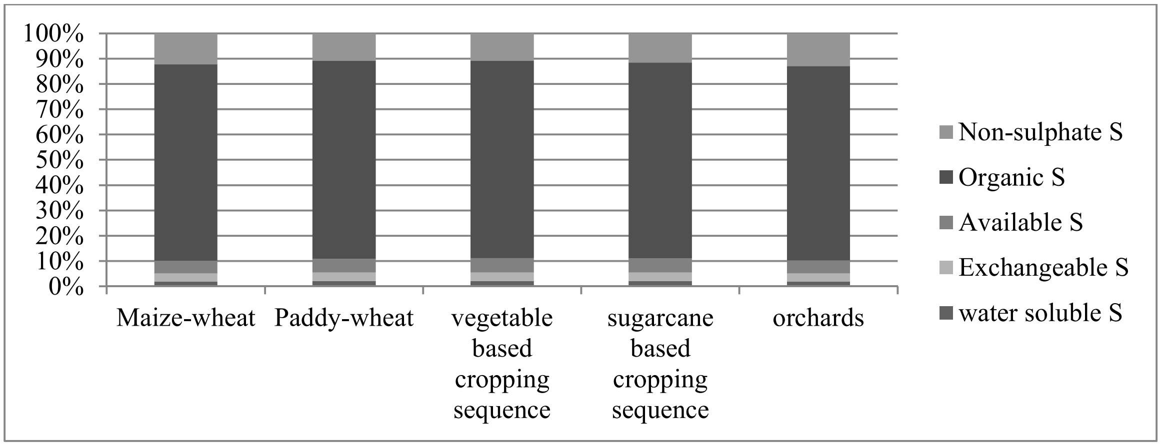

Figure 2: Per cent contribution of different forms of S to total S in soils under different land uses

(Figure 2). Exchangeable sulphur exhibited a significant positive correlation with organic carbon (r=0.84*), CEC (r=0.70*) and clay (r=0.84*) and significant negative with sand (r=-0.21*) (Table 3). The content of exchangeable sulphur was in agreement with that reported by Khalid et al., (2011) in soils of Pakistan and Anjali and Das (2012) in some soils of plain zone of Assam.

Available sulphur

Available sulphur in these soils ranged from 3.1 to 21.1 mg kg^{-1} with mean value of 9.8 mg kg^{-1}. On an average, it constituted 5.36, 5.75, 6.08, 5.81 and 5.41 per cent of total S in soils under maize-wheat sequence, paddy-wheat sequence, vegetable based cropping sequences, sugarcane based cropping sequences and orchards, respectively (Figure 2). Available S exhibited a significant positive correlation with organic carbon (r=0.80*), CEC (r=0.70*) and clay (r=0.80*) and significant negative with sand (r=-0.22*) (Table 3). The content of available sulphur was in line with that reported by Dhamak *et al.* (2014) and Majumdar and Patil (2016).

Organic sulphur

Organic sulphur content in these soils varied from 75.9 to 316.1 mg kg^{-1} with the mean value of 143.4 mg kg^{-1}. On an average, it constituted 81.76, 83.05, 82.78, 81.86 and 81 per cent of total S in soils under maize-wheat sequence, paddy-wheat sequence, vegetable based cropping sequences, sugarcane based cropping sequences and orchards, respectively (Figure 2). On an average, it constituted 82.56 per cent of total S in soils (Table 2). Organic S exhibited a significant positive correlation with organic carbon (r=0.79*), CEC (r=0.68) and clay (r=0.68*) and significant negative with sand (r=-0.21*) (Table 3). Similar observations were reported by *Patra et al.,* (2012) in different blocks of four districts of West Bengal and Sutaria *et al.* (2016) in soils of Rajkot District of Gujarat.

Non-sulphate sulphur

Non-sulphate sulphur content in these soils varied from 8.0 to 41.5 mg kg^{-1} with the mean value of 21.7 mg kg^{-1}. On an average, it constituted 12.88, 11.35, 11.42, 12.26 and 13.59 per cent of total S in soils under maize-wheat sequence, paddy-wheat sequence, vegetable based cropping sequences, sugarcane based cropping sequences and orchards, respectively (Figure 2). On an average, it constituted 12.03 per cent of total sulphur in soils (Table 2). Non-sulphate S exhibited a significant positive correlation with organic carbon (r=0.46*), CEC (r=0.58*) and clay (r=0.72*) and significant negative with sand (r=-0.24*) (Table 3). These observations are in conformity with those of Swarnakar and Verma (1978) in Bundelkhand soils.

Total sulphur

The total sulphur content in these soils varied from 75.5 to 281.9 mg kg^{-1} with the mean value of 155.6 mg kg^{-1}(Table 2). Total S exhibited a significant positive correlation with organic carbon (r=0.80*), CEC (r=0.68*) and clay (r=0.64*) and significant negative with sand (r=-0.25*) (Table 3). Similar findings have been reported by Dolui and Guhathakurta (2007) in soils from different agroclimatic region of West Bengal and Bhogal *et al*., (1996) in soils of Muzaffarpur and Samastipur districts of Bihar. It may be inferred from previously mentioned results that amount of S in each of its chemical pools differs within and between soils. Water-soluble and exchangeable sulphur is directly available to plants, while the mineralization of sulphate from organic sulphur also made an important contribution to plant uptake of sulphur. The forms of sulphur present in these soils are in the order of total S, organic S, non-sulphate S, available S, exchangeable S and water soluble S. The distribution of S forms in cultivated soils can be explained on basis of variation in soil properties affecting their content, soil mineralogy, soil weathering stage and dynamic equilibria between different forms. Organic S and non-sulphate S content constituted largest components of total S, mainly governed by organic carbon and clay content. It was found that all forms of S present in soils were significantly and positively correlated with each other (Table 4).

Conclusions

Perusal of the data indicated that the abundance of various forms of sulphur in these low base saturated soils was in the order of total S > organic S > non-sulphate S > available S > exchangeable S > water soluble S and their availability was influenced by various soil properties. The results indicated that different forms of sulphur in these soils follow each other and are inter-related within them.

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