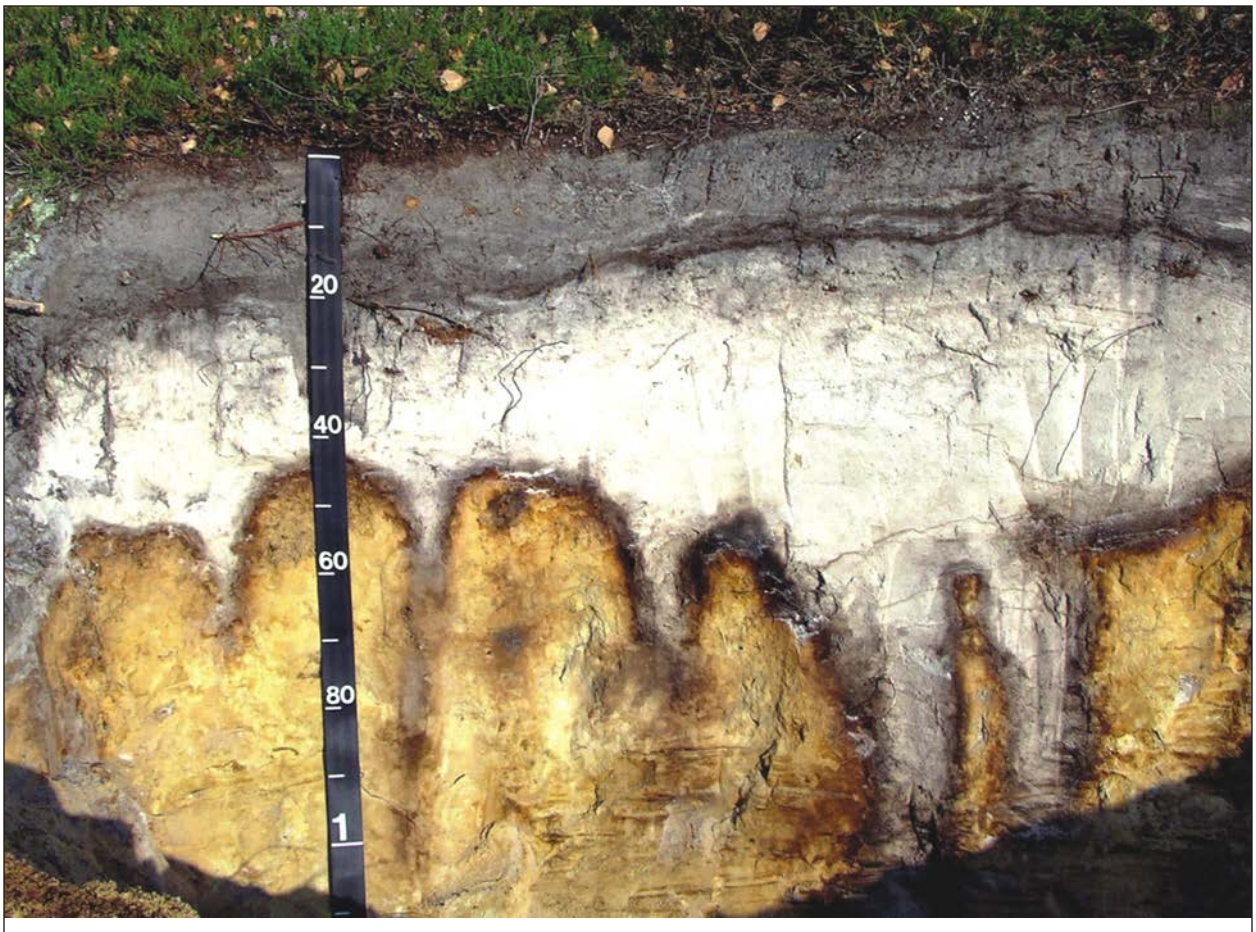

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Soil Microbial Activity and its Relation to Soil Indigenous Properties in Semi-arid Alluvial and Estuarine Soils of Mahi River Basin, Western India

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ABSTRACT

Several studies on the continental Quaternary sedimentation, stratigraphy and landscape evolution of the Mahi River basin exist, however, the microbial activity including its relation with soil physical and chemical properties has not been explored. In the present investigation, estuarine and alluvial soil microbial activity (as an index of soil enzymes i.e., dehydrogenase and protease) and its relation with soil properties such as Soil Organic Matter (SOM), Soil Moisture Content (SMC), soil texture (sand, silt and clay) and soil pH has been addressed. The study was conducted at 7 sites spread over 3 locations (2 were from alluvial zone and 1 was from estuarine zone), each sampled at various depths along a 30 km long stretch of the Mahi River in western India. High microbial activity was noticed in estuarine soils than in alluvial soils. Dehydrogenase activity in both alluvial and estuarine soils indicated positive correlations with SOM, SMC and a moderate correlation with clay content. On the contrary, the protease activity showed poor correlation with SOM, SMC and clay content of alluvial soils however, significant positive correlations were noticed in estuarine soils. No correlation was observed between these two enzymes. A negative correlation existed between soil depth and both the enzymes in alluvial soils. The findings demonstrate that SOM and SMC, clay content and soil depth are the important determinants for dehydrogenase activity (indicative of organic matter transformation) in both alluvial and estuarine soils, whereas the soil depth is the lone determinant for protease in alluvial soils and its correlation with other properties in estuarine soils is site specific.

Key words: Alluvial soils, estuarine soils, dehydrogenase, protease, specific enzyme activities

INTRODUCTION

Microbiology of the floodplains has received a lot of attention (Baldwin and Mitcheel, 2000; Gergel *et al*., 2002; Kang and Stanley, 2005). Microbial activity in floodplains can control the ecosystem and metabolism of rivers (Fischer and Pusch, 2001; Fischer *et al*., 2003) and is significantly influenced by variability in hydrologic regimes, flow dynamics, sediment movement (Baldwin and Mitcheel, 2000; Fischer *et al*., 2003) and chemical pollutants (Onweremadu and Nwufo, 2009). Investigations on the sediments of river channels have shown that microbial

activity is controlled by sediment structure, hydraulic conditions and availability of organic carbon and nitrogen (Fischer *et al*., 2005). Although microbial activity of river channels, streams, sediments and hyporheic zone are well studied, microbial activity of the semiarid alluvial plains is not yet established.

Soil enzymes are considered to be indicative measures of soil fertility (Zahir *et al*., 2001). Soil enzymes derived primarily from soil microbes are important due to the fact that they participate in elemental cycling and decomposition of organic residues and are considered fundamentally good indicators for soil quality (Abdalla and Langer, 2009; Kizilkaya *et al*., 2007; Venkatesan and Senthurpandian, 2006; Caldwell, 2005). Dehydrogenase is one such enzyme indicative of overall biological and microbial activity of soils (Quilchano and Maranon, 2002) because it is associated with living cells and is linked with microbial oxidoreduction processes (Alef and Nannipieri, 1995; Stepniewska *et al*., 2007) which are important for organic matter degradation and transformation. Dehydrogenase activity in soils is very sensitive to various natural and anthropogenic factors like soil aggregation, soil aeration status (Brzezinska *et al*., 2001), organic content (Gajananda, 2007; Tirol-Padre *et al*., 2006) devegetation (Bastida *et al*., 2006), agricultural management (Truu *et al*., 2008), addition of pesticides (Stepniewska *et al*., 2007), insecticides (Singh and Kumar, 2008) and heavy metal combined pollution (Gao *et al*., 2010). Soil proteases are extra-cellular enzymes produced mainly by bacteria which degrade proteins, release NH_4-N and are very important in nitrogen cycle (Sardans *et al*., 2008). Initial breakdown of proteins from the Soil Organic Matter (SOM) is virtually mediated by soil proteases. Estimation of proteases provides information on nitrogen mediated biochemical processes in the soil (Sardans and Penuelas, 2005).

Mahi River originates near Moripara in Dhar district of Madhya Pradesh and flows through the Precambrian Aravalli mountain range and the vast Gujarat alluvial plains and merges in the Gulf of Cambay. The Mahi River basin falls under semiarid climatic zone, a major climatic zone of India comprising 37% of the total geographical area of the country and the alluvial soils are under intense weathering as well as erosion which are significant processes in landscape evolution. In earlier studies, the Mahi river basin has been investigated for understanding Quaternary environmental and tectonic changes and their implications on the fluvial systems and landscape of the dry lands of Gujarat (Chamyal *et al*., 2003; Maurya *et al*., 2000). The significance of the exposed sedimentary records in the cliffy banks of the Mahi River is realized and used for reconstruction of Quaternary continental stratigraphy and understanding the geomorphic evolution of the Mahi River basin (Sridhar, 2007; Chamyal *et al*., 2003; Juyal *et al*., 2000). Since microbial activity is linked with several ecosystem processes including soil formation, weathering and organic matter transformation, it is important to understand the factors that control microbial distribution and activities in alluvial soils. Realizing this, the present study was initiated to investigate microbial parameters and their critical decisive determinants in the soils of alluvial plains of Mahi River in western India.

MATERIALS AND METHODS

Study site description and sample collection: The sites studied are located in the semi arid Mahi River basin, Western India (Fig. 1), with mean annual rainfall about 600 to 650 mm spanning three locations Rayka, Dodka and Mujpur. The alluvial zone of the Mahi River basin at Rayka (22° 26' 56.59"N, 73° 05' 16.95"E) comprises of distinct geomorphic units and alluvial deposits of Pleistocene and Holocene age (Juyal *et al*., 2000; Chamyal *et al*., 2003; Maurya *et al*., 2000; Rachna *et al*., 1998). River channel on the convex banks is bordered by cliffs rising about

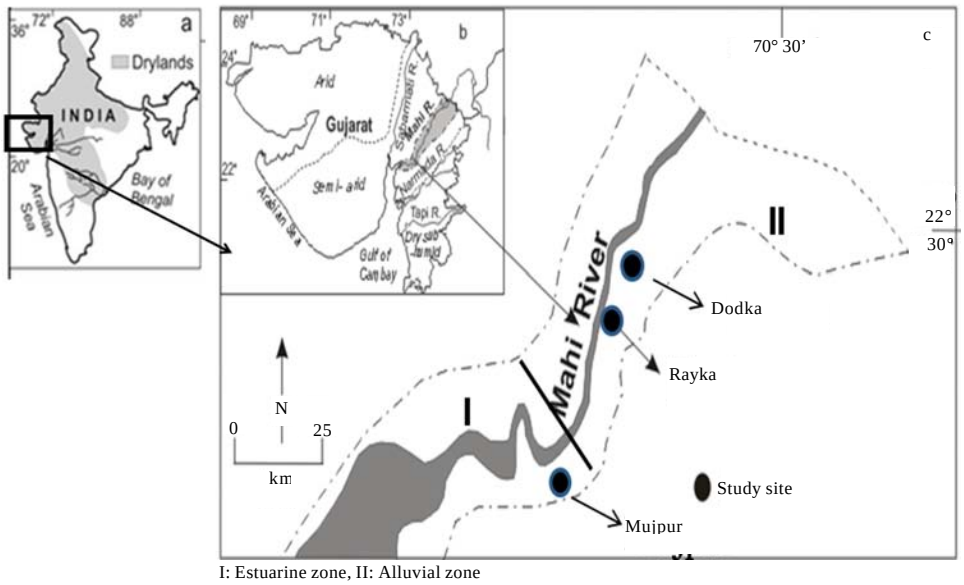

Fig. 1: Location map of the study area showing the study sites and generalised geomorphic and climatic zones. (a) Distribution of dry lands in India. (b) Major climatic zones and rivers of Gujarat and (c) Geomorphic zones in the Mahi River basin (after Rachna *et al*., 1998). Sites sampled are marked with filled circles

30-40 m from the river level (Juyal *et al*., 2000). The sediment and soil sequences along these cliffs have been dated back to 125 ka (Juyal *et al*., 2000). At Rayka, the sediments comprising these cliffs are deeply incised inland forming ravines exposing sediment sequences. The alluvial zone of the Mahi River basin at Dodka (22° 28' 54.0"N, 73° 06' 5.67"E) lies up stream of Rayka. The sediment sequence at Dodka is capped by aeolian deposits which show intense weathering. Significant soil erosion is also observed in Dodka section. In both Dodka and Rayka, landscape is covered with *Calotrophis procera, Zyzyphus nummulariea, Acasia* and grasses like *Heterophogan, Setaria* sp., *Cymbopogon* sp., *Digitaria* sp. and *Brachiaria* sp. Mujpur section lies in the estuarine zone located downstream of Rayka and is made up of sediments of mid to late Holocene forming a younger terraced surface.

A total of 33 triplicate composite samples at an interval of 25 cm from the three exposed sections at Dodka, Rayka and Mujpur were collected for the present study. Due to lot of heterogeneity at alluvial sites and varied stratigraphy, more number of samples (twenty seven) were collected from alluvial zone. However, only six samples were collected from the estuarine zone of Mahi River basin because of low heterogeneity. All the sites selected were unexposed to anthropogenic activities. Prior to the collection of soil samples, the sites were cleaned by scraping the surface layer. Due to difference in geomorphic settings, at Rayka 5 different sites (each harbouring distinct soil sequences) such as Rayka Ravine soil (RR), Rayka Ravine Red soil (RRR), Rayka aeolian soil (RW), Rayka Surface soil (RS) and Rayka surface Red soil (RD) were selected and a total of 22 samples were collected. These 5 sites represent the overall soil sequences developed over river borne sediments along the bank of Mahi River at Rayka. Eleven samples were collected from 3 sites

(RR, RRR and RW) at the Rayka section exposed along the Mahi River bank and remaining eleven samples were collected from other 2 sites (RS and RD) at a section exposed landward in a deeply incised ravine. Five samples were collected from Dodka section (D) and six samples from Mujpur (M) located in the estuarine zone of Mahi River. Due to distinct stratified soil successions that occurred in the exposed sites and the different thickness of the soil profiles, the material was available at different depths, therefore the gradient in depth was not same for all the samples. For example, at RW site, which is a soil profile developed over wind-borne material of above 75 cm thickness, the samples were collected up to a depth of 75 cm. Same case was observed in RRR but here the profile has been developed over a river-borne sediment layer measuring 125 cm. No distinct pedon was noticed below the 125 cm (D5) in the Dodka site which was comprised of loose fluvial sediments. Autoclaved polyethylene bags were used for sampling which were immediately kept on ice packs before being transported to the lab. All the samples were sieved (<4 mm), cleaned of visible roots and plant residues and stored at 4°C.

Determination of soil parameters: Soil samples were analysed for soil moisture content, pH, soil texture according to the standard protocols (Alef and Nannipieri, 1995). Soil Organic Matter (SOM) was determined by dichromate digestion method (Walkley and Black, 1934). All the determinations were performed in triplicate and values reported are mean with standard deviation.

Determination of soil enzymes: Dehydrogenase activity in soils was measured by following the reduction of 2,3,5-Triphenylotetrazolium Chloride (TTC) as an artificial electron acceptor to red-coloured formazons which were extracted and determined colorimetrically (Alef and Nannipieri, 1995). The amount of Triphenyl Formazan (TPF) extracted was calculated by reference to a calibration graph prepared from TPF standards.The dehydrogenase activity is expressed as μg of TPF g^{-1} 24 h^{-1} oven dried soil. Protease activity was determined by using the method given by Ladd and Butler (1972) with sodium caseinate as a substrate.

Statistical analyses: The results obtained were examined statistically for linear regression and Pearson product moment correlations by Origin 6.0 statistical software (Microcal Software, Inc). For identification of meaningful variables in the studied samples Principle Component Analysis (PCA) was carried out by using XLSTAT version 2009.6.01 (trade mark of Adinosoft).

RESULTS

Soil parameters: Characteristics of soil samples taken from 3 locations are summarized in Table 1. All the 33 soil samples were neutral to slight alkaline in nature with a pH ranging from 6 to 7.6. Mujpur soils were characterised by a high content of Soil Organic Matter (SOM), Soil Moisture Content (SMC) and clay (%) in comparison to the other two sites (Table 1). This may be due to geographical location of Mujpur section which is near the estuarine zone of Gulf of cambay where frequent back waters inundate during high tides.

Soil enzymes and their correlation to soil parameters: Dehydrogenase and protease activities of the 3 locations (Fig. 2) were varied with the sampling site and soil properties. Both the enzyme activities are comparatively high in Mujpur site indicating high microbial activity in the estuarine zone. Significant positive correlation was noticed between Dehydrogenase activity (cluster of 27

Table 1: Properties of soils used in this study. RR, RRR, RW, RS and RD are samples series collected at Rayka section. D and M are soils taken at Dodka and Mujpur respectively. Rayka and Dodka samples are obtained from alluvial zone of Mahi River where as Mujpur soils were representative of estuarine zone of Mahi River

Sample	Soil depth (cm)	pH	SOM (%)	SMC (%)	Sand (%)	Silt (%)	Clay (%)
Rayka							
RR1	0-25	7.4	1.90	5.0	33.3	46.6	20.8
RR2	25-50	7.1	1.70	5.0	31.1	47.1	21.8
RR3	50-75	7.0	1.40	5.0	46.6	40.0	13.4
RR4	75-100	6.9	1.25	5.0	42.6	45.3	12.1
RR5	100-125	7.0	1.20	4.0	46.6	40.6	12.8
RRR1	0-25	7.0	3.60	6.0	45.3	41.3	13.4
RRR2	25-50	7.5	2.20	5.0	47.3	41.3	11.4
RRR3	50-75	7.3	2.30	5.0	45.0	42.6	11.4
RW1	0-25	6.0	2.50	5.0	42.6	43.3	14.1
RW2	25-50	6.8	2.90	6.0	45.2	41.3	13.7
RW3	50-75	6.9	1.80	5.0	44.6	45.3	10.1
RS1	0-25	6.9	1.43	4.0	42.0	45.3	12.1
RS2	25-50	7.1	1.40	4.0	44.6	41.3	14.1
RS3	50-75	7.3	1.20	4.0	44.6	42.6	12.8
RS4	75-100	6.9	1.40	4.0	46.0	42.0	12.0
RS5	100-125	7.2	0.93	5.0	46.0	42.6	11.4
RS6	125-150	7.2	0.40	4.0	47.3	41.3	11.4
RD1	0-25	7.4	2.00	6.0	41.3	45.3	13.4
RD2	25-50	7.5	2.00	6.0	42.4	42.0	15.4
RD3	50-75	7.3	2.63	7.0	41.3	40.6	18.1
RD4	75-100	7.2	2.90	6.0	45.3	40.6	14.1
RD5	100-125	7.2	2.66	6.0	41.3	41.3	17.4
Dodka							
D1	0-25	7.4	1.80	6.0	18.4	68.0	14.6
D2	25-50	7.4	1.20	5.0	20.0	73.3	12.5
D3	50-75	7.2	1.40	5.0	18.6	67.2	14.2
D4	75-100	7.5	1.50	5.0	19.5	67.3	14.2
D5	100-125	7.6	1.70	5.0	20.0	61.3	18.7
Mujpur							
M1	0-25	7.2	1.70	5.0	22.6	40.0	36.4
M2	25-50	7.2	2.30	6.0	21.3	42.6	36.1
M3	50-75	7.2	2.30	8.0	19.3	44.0	36.7
M4	75-100	7.2	2.50	11.0	20.0	42.0	38.0
M5	100-125	7.2	3.00	20.0	20.0	40.0	40.0
M6	125-150	7.3	3.70	22.0	18.2	40.0	40.8

samples from both Rayka and Dodka) and SOM (Fig. 3, $r = 0.786$, $p<0.001$, $n = 27$) in alluvial soils and it is very well correlated in estuarine zone (Fig. 3 inset, $r = 0.955$, $p<0.001$, $n = 6$). Protease activity does not show any significant relation with SOM (Fig. 3, $r = -0.312$, $p>0.11$, $n = 27$). However, in estuarine soil samples, a positive correlation with SOM (Fig. 3) was obtained and was significant ($r = 0.98$, $p<0.001$, $n = 6$).

Positive correlation was noticed between dehydrogenase and SMC ($r = 0.56$, $p<0.001$ $n = 27$) in alluvial soils (data not shown). No statistical relationship is seen between overall protease activity and SMC ($p>0.05$) in alluvial soils however the positive correlation found in estuarine soils (Fig. 4, $r = 0.94$, $p<0.001$, $n = 6$) and this is in agreement with other results indicating that the Mujpur section is microbiologically more active than other two sites.

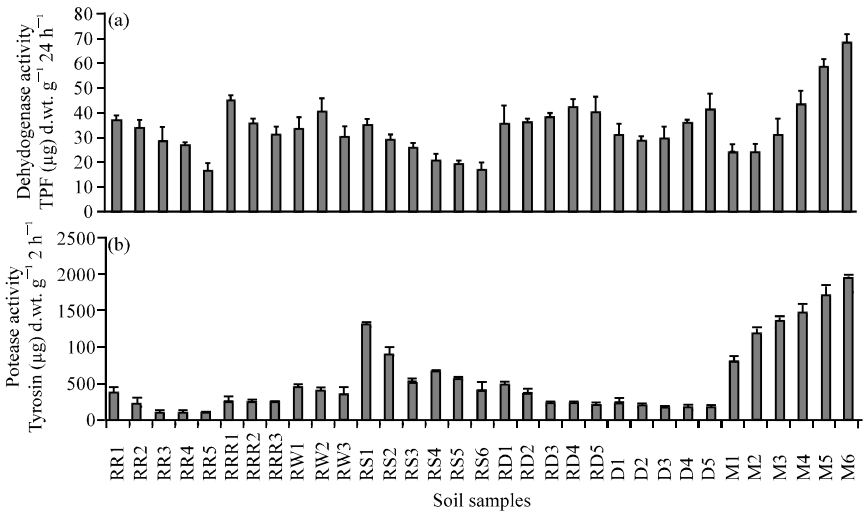

Fig. 2: Dehydrogenase and protease activities of soil samples. (a) Dehydrogenase activities of alluvial (from RR1-D5) and estuarine samples (M1-M6). (b) Protease activities of alluvial (from RR1-D5) and estuarine (M1-M6) samples

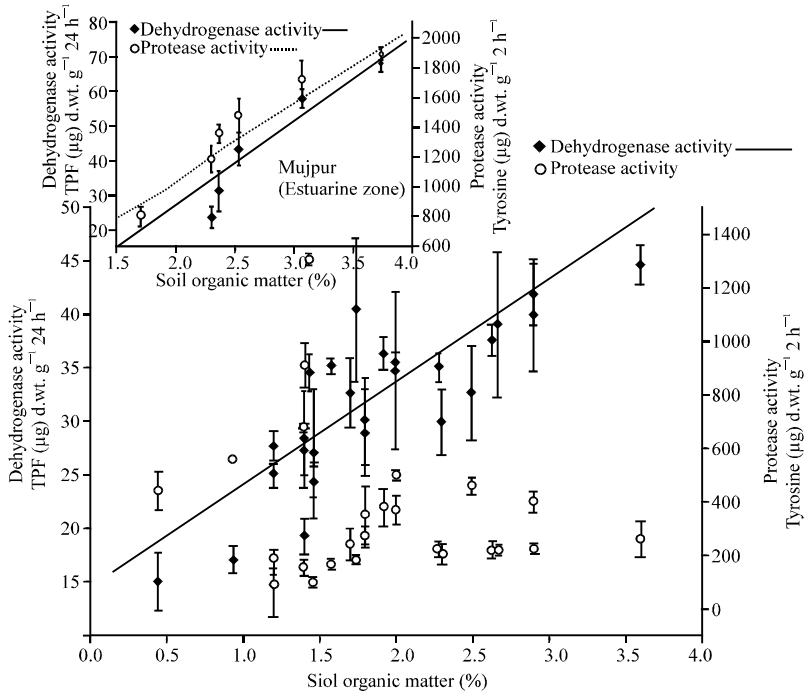

Fig. 3: Correlation of dehydrogenase and protease activities with SOM in alluvial soils. Regression line shown for significant positive correlation in case of dehydrogenase activity ($r = 0.786$, $p<0.001$), whereas no correlation was noticed with protease activity. Inset shows data for estuarine (Mujpur soil) samples, where both dehydrogenase and protease activities showed significant positive correlation ($r = 0.95$ and $r = 0.98$ respectively) with SOM at $p \leq 0.001$

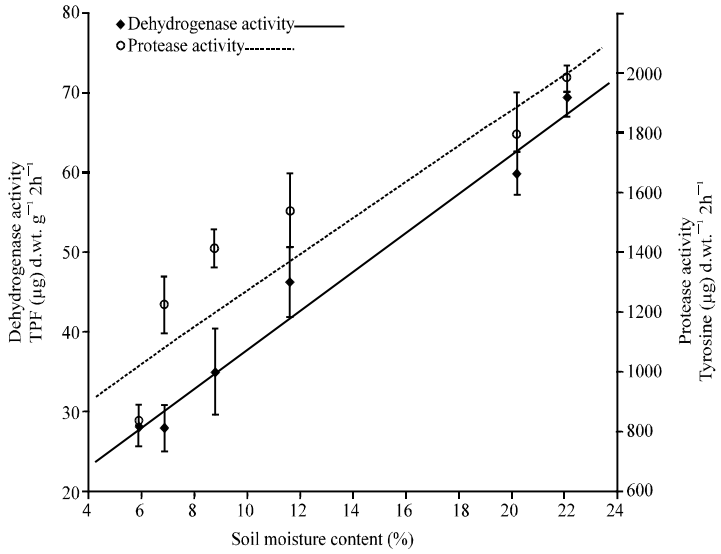

Fig. 4: Correlation of dehydrogenase and protease activities with SMC in estuarine soils (r = 0.99 and r = 0.94 respectively) at p≤0.001

Table 2: Pearson product moment correlation between soil enzymes and soil depth

	Protease activity		Dehydrogenase activity		Protease activity/C		Dehydrogenase activity/C	
Sample site	r-value	p-value	r-value	p-value	r-value	p-value	r-value	p-value
RR	-0.89	0.04	-0.97	0.001	-0.61	0.266	-0.95	0.01
RRR	-0.98	0.01	-0.98	0.012	0.28	0.817	-0.83	0.37
RW	-0.99	0.002	-0.34	0.07	0.93	0.239	-0.62	0.56
RS	-0.87	0.002	-0.97	0.001	0.46	0.358	-0.83	0.03
RD	-0.88	0.041	-0.83	0.07	-0.80	0.100	0.84	0.071
D	-0.66	0.21	-0.83	0.07	0.64	0.24	0.15	0.80
M	0.98	0.001	0.96	0.001	0.80	0.051	0.95	0.002

Protease activity: Tyrosine (µg) d.wt. g^{-1} 2 h^{-1}., dehydrogenase activity: TPF (µg) d.wt. g^{-1} 24 h^{-1}, Protease activity/C: Tyrosine (µg) d.wt. g^{-1} C 2h^{-1}, Dehydrogenase activity/C: TPF (µg) d.wt. g^{-1} C 24 h^{-1}

The other variables considered in this study are the sand, silt and clay content and soil depth. Since soils were collected at different depth gradients, correlations have been made for individual sites. Soil depth showed a negative correlation with dehydrogenase and protease activities in alluvial zone (sites RR, RRR, RW, RS, RD and D, Table 2) however, in estuarine zone (site M), significant positive correlations were noticed with dehydrogenase activity (r = 0.98, p<0.001, Table 2) and with protease activity (r = 0.96, p<0.001, Table 2). The dehydrogenase activity shows a moderate positive correlation with clay content of the soils (Fig. 5, r = 0.52, p<0.004, n = 27). No significant correlation was however, noticed with protease activity (r = -0.45, p<0.177, n = 27) barring a positive correlation in Mujpur site (Fig. 5, r = 0.92, p<0.001). No apparent relation was found for both enzymes with pH, sand and silt content of the soils at p level 0.1 (data not shown) however a negative correlation of dehydrogenase activity and protease activity with sand proportion (r = -0.85, p<0.02, n = 6, r = -0.94, p<0.004, n = 6, respectively) was noticed in Mujpur section and it is site specific.No significant correlation was observed between the two enzymes

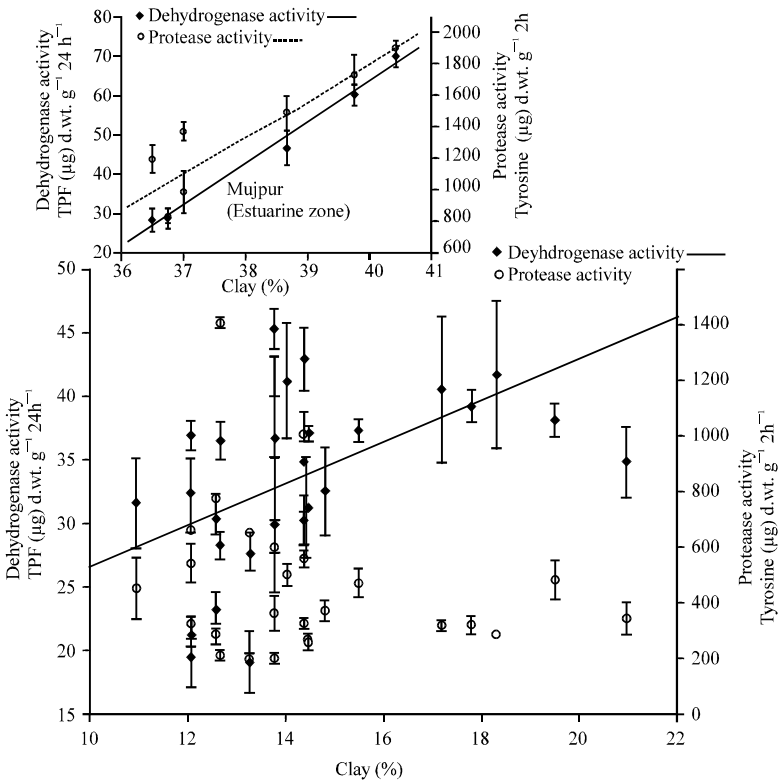

Fig. 5: Correlation of dehydrogenase and protease activities with clay content in alluvial soils. Regression line shown for positive correlation in case of dehydrogenase activity ($r = 0.52$, $p<0.004$) where both dehydrogenase and protease activities showed significant positive correlation ($r = 0.99$ and $r = 0.92$ respectively) with clay at $p = <0.001$

(Fig. 6, $r = -0.32$, $p>0.1$, $n = 27$) in alluvial soils. On the contrary significant positive correlation was observed between dehydrogenase and protease in estuarine zone of Mahi River (Fig. 6, $r = 0.94$, $p<0.001$, $n = 6$).

Since the studied soils possess variable amounts of SOM, specific enzyme activity indices were calculated per unit of total C. These activity indices were correlated with soil parameters (Table 3) and the results show that dehydrogenase specific activity is moderately correlated with clay content and significantly correlated with SMC and SOM in both alluvial and estuarine soils (Table 3). These results are in agreement with enzyme activity results, indicating that SMC and SOM content are critical determinants of dehydrogenase activity. Protease specific activity in the alluvial soils do not show any correlation with soil indigenous properties however a strong correlation was observed with SOM and clay percentage in estuarine soils ($r = 0.857$, $p = 0.02$ and $r = 0.92$, $p<0.009$, respectively Table 3).

Principle Component Analysis (PCA) is a variable reduction method which can be used to identify groups of observed variables that tend to cluster together. Present data were subjected to PCA analysis and principle components were extracted by Scree test from both alluvial and estuarine soils (Fig. 7, b). In both the cases, the first two components displayed Eigen values greater than 1.5. This suggested that the first two components were meaningful. Therefore, only the first two components were retained for rotation (varimax orthogonal). Combined, components

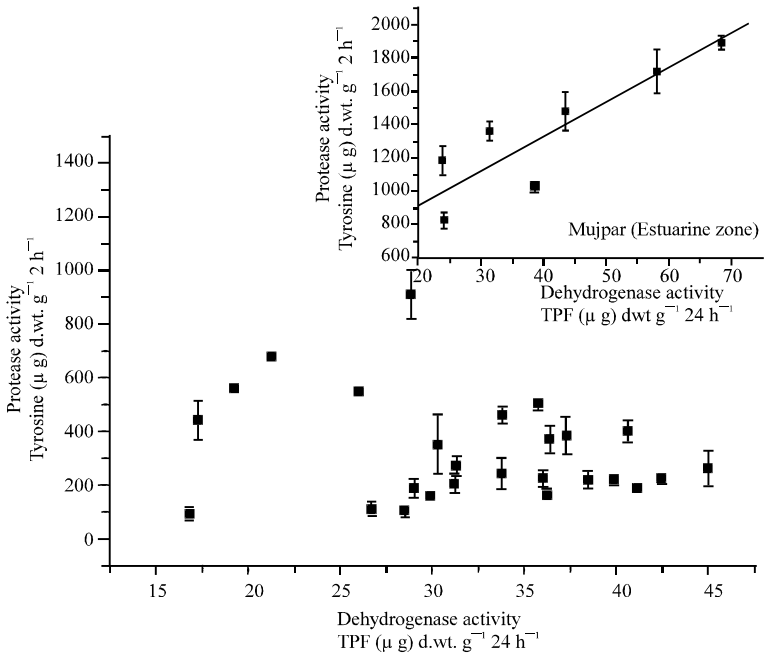

Fig. 6: Correlation between dehydrogenase and protease activities was not found in alluvial soils however inset data shown for estuarine samples and a linear strong correlation (r = 0.94) was observed among both the enzymes at $p \leq 0.001$

Table 3: Correlations between soil characteristics and specific enzyme activity indices in semiarid alluvial and estuarine soils

	Alluvial soils				Estuarine soils			
	Dehydrogenase		Protease		Dehydrogenase		Protease	
Soil parameters	r-value	p-value	r-value	p-value	r-value	p-value	r-value	p-value
SOM	0.998	0.0001	-0.705	0.001	0.999	<0.001	0.683	0.135
SMC	0.706	0.001	-0.426	0.02	0.933	0.006	0.857	0.029
Sand	0.171	0.393	-0.233	0.241	-0.793	0.059	-0.534	0.276
Silt	-0.257	0.195	0.273	0.169	-0.417	0.411	-0.715	0.111
Clay	0.234	0.241	-0.065	0.746	0.897	0.015	0.921	0.009
pH	0.0665	0.742	0.159	0.43	0.429	0.396	0.797	0.057
Dehydrogenase activity	-	-	-0.371	0.056	-	-	0.667	0.148
Protease activity	-0.193	0.335	-	-	0.667	0.148	-	-

1 and 2 of alluvial soil variables accounted for 67.19% of total variance (Fig. 7a) whereas combined components 1 and 2 of estuarine soil variables accounted for 90.63% of total variance (Fig. 7b). PCA plots (Fig. 7a, b) indicate that SMC, SOM, clay, dehydrogenase of both alluvial and estuarine zone form a closer cluster and hence are correlated with each other whereas sand, silt and pH showed different patterns and are scattered from the cluster. Strong correlation among both dehydrogenase and protease was observed in estuarine soils (Fig. 7b).

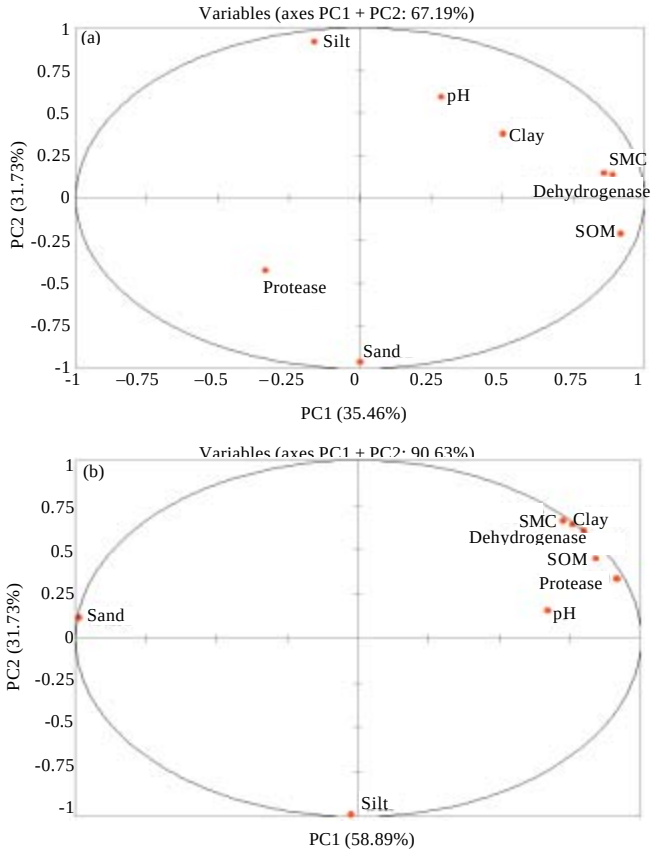

Fig. 7: Principle Component Analysis (PCA) for soil properties and enzymes. (a) PCA loading plot of alluvial zone variables. (b) PCA loading plot of estuarine zone variables

DISCUSSION

The activities of soil enzymes (dehydrogenase and protease) and their relation to soil characters were investigated in semiarid alluvial and estuarine soils around Mahi River basin. Both the enzyme activities were relatively high in estuarine soil samples indicating high microbial activity as well as high soil quality in estuarine zone. The enzyme dehydrogenase being one of the principle agent in the degradation of SOM (Tabatabai, 1994), it is inferred that SOM transformation in estuarine zone (Mujpur soils) is more than other two sites (Rayka and Dodka). Generally, protease activity depends on the distribution of proteolytic bacteria and the amount of proteinaceous substrate availability in the SOM. The results of protease activity indicate that proteolytic bacteria and the amount of proteinaceous substrates are comparatively high at Mujpur which lies in estuarine zone.

Present findings demonstrate that dehydrogenase activity is sensitive to SOM, SMC, clay and soil depth. The SOM is one of the critical determinative parameter of soil dehydrogenase because organic matter is substrate for microbial dehydrogenase activity. Gajananda (2007) demonstrated similar relationship between organic carbon and dehydrogenase ($r = 0.85$, $p<0.001$) and stated that

organic C is an important factor in controlling the development of dehydrogenase in arctic soils. Similar kind of observation was made by Tirol-Padre *et al.* (2006) during his study on organic amendments on soil hydrolytic enzymes. We infer that the immobilization of organo-mineral complexes by clay minerals allows retention of substrate to dehydrogenase. In contrast the protease activity is poorly correlated with SOM in alluvial zone. This may be due to either low amount of proteinaceous matter in SOM or less distribution of proteolytic bacterial population in studied semiarid alluvial soils.

Mujpur is situated in the estuarine zone of Mahi River; it gets inundated frequently during annual floods, high tides and subsequently high availability of substrate enhancing the protease activity. Multiproxy study on Mujpur section may provide meaningful information in respect of enzyme dynamics vis-a-vis temporal changes.

Theoretically, a general consideration is that soils with high SMC content should possess high dehydrogenase activities because SMC enhances the microbial activities and dehydrogenase exists in soils as integral parts of intact cells. This was seen in Mujpur soils where SMC is positively correlated with its corresponding dehydrogenase activity (Fig. 4). Brzezinska *et al.* (2001) determined the relationship between the enzyme activity and soil aeration parameters in a pot experiment with barley vegetation and envisaged a positive relation between SMC and dehydrogenase activity ($r = 0.59$). Similar kind of observation was found in the present study (Fig. 4).

In accordance to earlier studies (Griffiths *et al.*, 2003), present results also showed a significant negative impact of soil depth on hydrolytic enzymes. Niemi *et al.* (2005) demonstrated a negative correlation between soil depth and enzyme activities and positive correlation between SOM and enzyme activities. In previous studies Sardans and Penuelas (2005) found a negative correlation between hydrolytic enzymes and soil depth. The present study and obtained data are in general agreement to their observations (Table 2). However, an increase in dehydrogenase with depth in the Mujpur section is suggestive of the increased enzymatic activity of anaerobic and facultative bacteria. Increase in protease activity with depth at Mujpur may be due to increased substrate availability and microbial activity. Similar kind of observations were made by Wright and Reddy (2001) and reported that the decreased protease and glucosidase activity with depth is due to decrease in substrate quality along with depth.

Both the enzymes in alluvial soils are independent of each other (Fig. 6) indicating soil organic matter transformation and initial breakdown of proteins are self regulated processes in alluvial systems. However, a correlation between higher dehydrogenase activity and higher protease activity was observed in Mujpur soils (Fig. 2 and 6) indicating high metabolic state of the estuarine soils. Initial organic matter transformation by dehydrogenase during microbial respiration made available substrate to protease and subsequently higher protease activity achieved in estuarine zone. In contrast, the alluvial site may be lacking a high amount of proteinaceous substrate in its integral part of SOM.

We presume that lower soil enzyme activities in alluvial soils were associated with progressive soil erosion. It has been demonstrated that dehydrogenase activity can be used as a sensitive marker of soil degradation in semiarid Mediterranean region of Spain (Garcia *et al.*, 1997). In the same study it was found that no correlation between the dehydrogenase activity of the soils and organic matter content ($r = 0.32$, $p = 0.18$) and it is contradictory to present findings which are showing positive correlation between dehydrogenase and SOM ($r = 0.52$, $p<0.004$, $n = 27$) in the semiarid alluvial zone which is under intense weathering. In another investigation which is on soil

quality degradation processes along a deforestation chronosequence in the Ziwuling area, China, it was found that the soil erosion was the primary process responsible for the degradation of soil physical, chemical and microbiological properties (An *et al.*, 2008). However, they have studied alkaline phosphatase activity and invertase activity. In another report from northern China (Yong-Zhong *et al.*, 2005), decreased soil enzyme activities were observed in a degraded sandy grass land however their studies were mainly focused on influences of continuous grazing and livestock exclusion on sandy grass land soil erosion. Although restricted to a limited number of soils, the present data suggests that, dehydrogenase and protease activities could be considered as indicators for intense erosion of semiarid alluvial soils.

In the alluvial soils, the decrease in the activity of soil enzymes with involved in recycling of nitrogen and carbon may effect long term soil nutrient availability and reducing the nutrient supply to plants. Moreover in both alluvial and estuarine ecosystems, oxidation of organic content and subsequent transformation could be depending on SMC, clay and soil depth.

CONCLUSIONS

Two soil enzymes dehydrogenase and protease showed different relationships with soil properties depending upon the alluvial and estuarine zones. SOM, SMC, clay content and soil depth are the main determinants for soil dehydrogenase activity and subsequent organic matter transformation in both zones. Soil protease activity and its critical determinates were found to be site specific. Relatively estuarine zone showed high microbial activity as compared to alluvial zone in the semiarid Mahi River region.

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