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Response of short-duration pigeonpea to nitrogen application after short-term waterlogging on a Vertisol

Ryoichi Matsunaga *, Osamu Ito, Satoshi Tobita [1], Theertham P. Rao, Chris Johansen

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, A.P.502 324, India

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Abstract

Short-duration pigeonpea suffers from waterlogging damage following heavy rainfall at the pre-flowering stage on soils with high clay content, such as Vertisols. Effects of short-term waterlogging (3 d) on shoot and root growth of short-duration pigeonpea grown on a Vertisol field were quantified, and the alleviation of waterlogging damage by top-dressing of nitrogen fertilizer was examined.

Reduced leaf chlorophyll, increased senescence and abscission of lower leaves were observed within 3 d of the initiation of waterlogging. Root growth and symbiotic N_2 fixation were also severely impaired. Root distributions of waterlogged plants were shallower than those of the control during the subsequent recovery period because new adventitious roots were formed in the shallow rather than deep soil layer. Yield of waterlogged crops was significantly smaller than the control.

Top-dressing of nitrogen at one day after the termination of waterlogging alleviated waterlogging damage either completely or partially. Leaf chlorophyll and shoot dry mass of waterlogged plants were 78 and 84% of the values in control plants immediately after waterlogging but recovered to 92 and 98% of the control values at the pod-filling stage with a top-dressing of 50 kg N ha^{-1}. Nitrogen application promoted root growth in the shallow soil layers during the first 11 d after application, and in the deeper soil layers during the subsequent 16 d. Total nodule activity was significantly reduced by 100 kg N ha^{-1}, but increased by 50 kg N ha^{-1} around one month after the top-dressing. The reduction in seed yield was largely compensated for by 50 kg N ha^{-1}, because of recovery from waterlogging damage to shoot and root growth involving increased nodule activity.

Keywords: Nitrogen top-dressing; Pigeonpea; Root growth; Symbiotic N_2 fixation; Vertisol; Waterlogging

1. Introduction

Short-duration pigeonpea (4–5 months to maturity) is being increasingly used in India, because of the high potential for developing new and productive cropping systems, compared with traditional cropping systems using medium- (5–6 months) or long-duration (6–9 months) pigeonpea (Panwar and Yadav, 1981; Kumar Rao and Dart, 1987). Short-duration pigeonpea is less affected by terminal drought stress, which is one of the important factors that limit seed yield in long-duration types (Johansen et al., 1989). Paradoxically, short-duration pigeonpea suffers from waterlogging damage following heavy rainfall on clay soils such as Vertisols (Reddy and Virmani, 1981). Chauhan (1987) reported that pigeonpea was very susceptible to water-

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* Corresponding author. Present address: Japan International Research Center for Agricultural Sciences (JIRCAS), Ohwashi 1-2, Tsukuba, Ibaraki 305, Japan.

[1] Okinawa Branch, Japan International Research Center for Agricultural Sciences (JIRCAS), Ishigaki, Okinawa 907, Japan.

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logging and that nearly 50% of waterlogged plants were killed by a 4-d treatment.

In most leguminous crops leaf chlorosis and senescence prevail after the initiation of waterlogging, and damage seems to be more severe than in cereal crops (Cannell et al., 1979). Root growth is also impaired by waterlogging (Cannell et al., 1979; Heatherly and Pringle, 1991; Pardales et al., 1991; Thomson et al., 1992). In cereal crops waterlogging restricts seminal root growth, causes a breakdown of root tissues and reduces root mass. In contrast, it promotes the formation of nodal roots from the shoot base in wheat (Trought and Drew, 1980), oats (Cannell et al., 1985), sorghum (Pardales et al., 1991) and barley (Cannell et al., 1984). Few studies have reported the effect of waterlogging on the root distribution in field-grown leguminous crops (Cannell et al., 1985). Since pigeonpea is well adapted to the semi-arid tropics, several physiological studies have been carried out on drought resistance (Muchow, 1984; Flower and Ludlow, 1987; Lopez et al., 1988; Johansen et al., 1989). However, there have been relatively few studies on the response of pigeonpea to waterlogging (Chauhan, 1987; Matsunaga et al., 1992).

Depression of nitrogen uptake after waterlogging limits the growth and grain yield of cereal crops (Watson et al., 1976; Cannell et al., 1985; Veen, 1988), soybean (Nathanson et al., 1984; Sugimoto et al., 1988b) and pigeonpea (Matsunaga et al., 1992). Therefore, nitrogen application can compensate partially or completely for the reduction of grain yield due to waterlogging damage by promoting tillering in cereals or increasing the rate of photosynthesis in soybean or both (Watson et al., 1976; Cannell et al., 1985; Veen, 1988; Sugimoto et al., 1989). There has, however, been no report on the influence of nitrogen application to waterlogged pigeonpea.

In India nearly 6 Mha, especially of Indo-Gangetic alluvium and Vertisols, are prone to waterlogging during the rainy season (Chauhan, 1987). According to the meteorological study of Reddy and Virmani (1981), waterlogging is a major constraint to rainy season crops on soils with high water-holding capacity. Sinha (1981) postulated that low yield of pigeonpea in some areas may be due to waterlogging. In the present study, we attempted to quantify the effects of short-term waterlogging (3 d) and top-dressing with nitrogen fertilizer on shoot and root growth. We also investigated if nitrogen application might alleviate yield reduction due to waterlogging, because breeding of new varieties tolerant to waterlogging is not completed.

2. Material and methods

Short-duration pigeonpea (*Cajanus cajan* (L.) Millspaugh cv. ICPL 87) was sown on a Vertisol at ICRISAT Center on 17 June 1991 and 18 June 1992 The soil surface (0-30 cm) was a calcareous heavy clay, a common property of Vertisols (Reddy and Virmani, 1981). Ten days before sowing, single superphosphate and urea were broadcast at 60 kg P and 25 kg N ha^{-1}, and incorporated into the soil to 20 cm depth by disc ploughing. Seeds were sown 15 cm apart in two rows on either side of ridges spaced at 60 cm (i.e. two rows on a ridge, and then 15×30 cm spacing). At 14 d after sowing plants were thinned to one plant per hill.

Treatments were allocated in the field as a split-plot design with three replicates. Main plots (9×30 m in 1991 and 9×20 m in 1992) were control (no waterlogging) and waterlogging treatments, and subplots (9×10 m) were N treatments. Before the waterlogging treatment, subplots were enclosed by earthen bunds to retain water on the soil surface. Waterlogging was imposed at the pre-flowering stage in August of both years when leguminous crops are very susceptible to waterlogging (Minchin et al., 1978; Cannell et al., 1979; Sugimoto et al., 1988a). The treatment was applied by furrow irrigation on the morning of 12 August 1991, and 20 August 1992. Water was applied until it reached around 5 cm above the tops of ridges. This level was maintained by adding water as necessary, until noon of 15 August 1991 and 23 August 1992, respectively. One day after the termination of waterlogging (DAW), urea was top-dressed at 0, 50 and 100 kg N ha^{-1} (referred to as N0, N1 and N2) to each subplot in 1991, and at 0 and 50 kg N ha^{-1} (N0 and N1) in 1992.

Oxygen concentration in the soil air at 20 cm depth was monitored every day during 1 to 29 August 1991 and on every second day from 10 August to 10 September 1992 with an oxygen analyzer (LC700F type, Toray Engineering Limited, Japan) as an index of soil aeration. Around 5 ml of soil air was collected with a plastic syringe at 20 cm depth through glass tubes (inner volume 0.1 ml) that had been installed in both control and waterlogged subplots with N1 one week before measurements began. The oxygen concentration was regarded as 0% when soil air could not be sampled during waterlogging and, in 1992, frequent rainfall.

Incidence of *Phytophthora* blight was negligible in most plots in 1991, but it severely damaged plants in some parts of several subplots in 1992, due to frequent precipitation in early August. Therefore, in 1992, sampling of plants was made from areas not affected by *Phytophthora* blight, to avoid the direct pathological effect on the physiological and morphological response of pigeonpea to waterlogging.

Shoot samples were taken from two 1.2-m rows at 10- to 14-d intervals after waterlogging, and their oven-dried mass determined. Leaf discs (9 mm diameter) were punched with a cork borer from the fourth leaf below the uppermost unfolded leaf on the main stem. The total chlorophyll concentration was determined by spectrophotometric measurement following extraction with 80% acetone (MacKinney, 1941).

Three soil columns were taken, respectively, vertically below a plant, and at 10 and 20 cm away from plants in the interrow of all subplots. Sampling was carried out to 100 cm depth with a 5.08-cm diameter auger on 41 DAW in 1991 and 1, 12 and 28 DAW in 1992. The soil columns were sectioned into 10-cm layers and carefully washed with water to extract the roots. Root length was measured with a root length scanner (Comair, Commonwealth Aircraft Corporation Limited, Australia) after roots were separated from other plant debris.

Soil monoliths were taken to determine nodule activity by acetylene reduction assay on 12 DAW in 1991, and at 1, 12 and 28 DAW in 1992. Soil monoliths of 30×30×30 cm were carefully taken to span middle ridge to middle row in all subplots. Roots and nodules were immediately washed from the soil and placed into incubation bottles. After the addition of acetylene (10% *v/v*) into bottles they were incubated at 30°C for one hour to determine ethylene evolution with a gas chromatograph with a FID detector (F33 type, Perkin-Elmer Limited, UK).

Seed yield was determined by harvesting mature pods from around 10 m^2 in all plots twice on 30 October and 2 December 1991, and from 5 to 8 m^2 on 4 November and 3 December 1992.

3. Results

3.1. Oxygen concentration in soil air

Oxygen concentration in soil air at 20 cm depth was not affected by rainfall in 1991 and remained almost constant at around 20% in both control and waterlogged plots before waterlogging (Fig. 1A). No soil air was sampled during the 3-d waterlogging treatment. Oxygen concentration was significantly lower in waterlogged than in control plots for 4 DAW. Thereafter, oxygen concentration recovered quickly to 20%, due to minimal rainfall during this period.

Because of frequent rainfall before and after the beginning of oxygen measurement in 1992 (Fig. 1B), no gas could be sampled from the soil in either control or waterlogged plots for the first eight days (10 to 17 August, Fig. 1B), even though no free water stood on any experimental plot. The concentration in control plots recovered to 16% at the initiation of waterlogging and stayed around 20% thereafter, except at the beginning of September. Gas samples could not be extracted for 4 days (waterlogging period + 1 day after the treatment). Oxygen concentration in waterlogged plots recovered more slowly in 1992 compared with 1991,

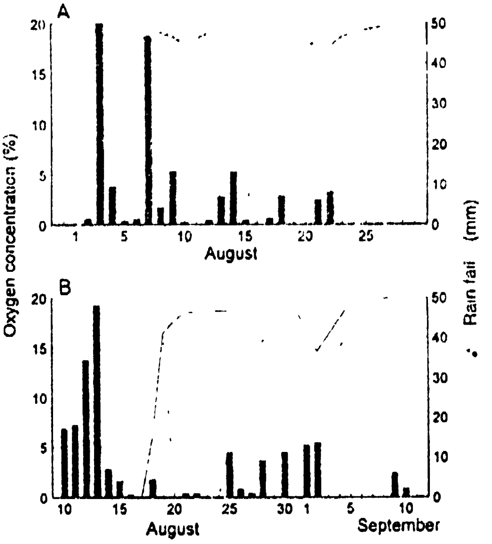

Fig. 1. Daily rainfall (columns) and seasonal change in oxygen concentration in soil air at 20 cm depth in 1991 (A) and 1992 (B). Oxygen concentration in control (solid line) and waterlogging (broken line) plots; duration of waterlogging treatment (A) 12–15 August 1991 and (B) 20–23 August 1992.

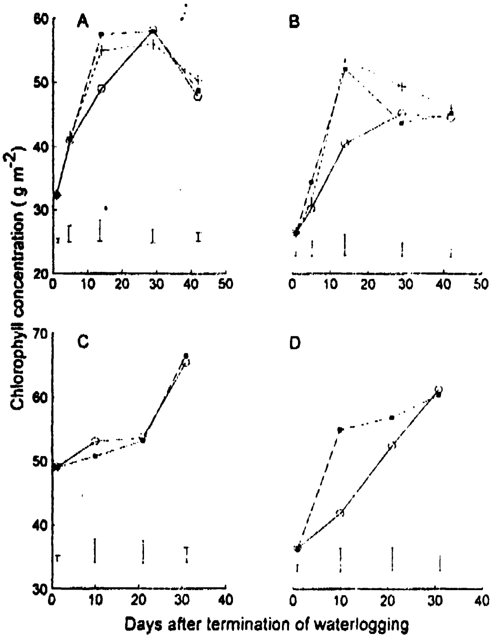

Fig. 2. Effect of N top-dressing on chlorophyll concentration in mature upper leaves after waterlogging in 1991 (A: control, B: waterlogging) and 1992 (C: control, D: waterlogging). N0 (○), N1 (■) and N2 (+) treatments. Vertical bars are standard errors of means for the comparisons at any treatment combination.

and reached almost the same level as in control plots by 10 DAW.

3.2. *Leaf chlorophyll and shoot growth*

Chlorophyll concentration in mature upper leaves of control plants increased rapidly from 1 (around 14 d before flowering) to 30 DAW (early pod-filling stage), but decreased at the last measurement (42 DAW) in 1991 (Fig. 2A). The seasonal increase was much slower for waterlogged plants without N top-dressing (Fig. 2B). The chlorophyll concentration of both control and waterlogged plants was significantly enhanced by N top-dressing (N1 and N2 treatments) at 14 DAW. This was particularly distinct for waterlogged plants which showed no difference in leaf color from controls at this stage. However, the effect of N top-dressing on leaf chlorophyll disappeared by 30 DAW for control and 40 DAW for waterlogged plants. Leaf chlorophyll concentration in control plants was not affected by N top-dressing in 1992 (Fig. 2C), while concentration in waterlogged plants increased significantly at 10 DAW with N top-dressing. This effect disappeared, however, by 30 DAW (Fig. 2D).

Shoot growth became much slower after waterlogging without N top-dressing in both 1991 and 1992 (Fig. 3). Shoot mass of waterlogged plants was increased with N1 treatment at 30 and 40 DAW (Fig. 3B). However, N2 treatment did not increase shoot mass of waterlogged plants. The effect of N top-dressing was not significant for control plants during the sampling period (1 to 40 DAW; Fig. 3A). Shoot growth of waterlogged plants was enhanced by N top-dressing after 30 DAW in 1992 (Fig. 3D). There was considerable increase in shoot mass of control plants at 20 DAW but the difference was lost by 30 DAW (Fig. 3C).

3.3. *Spatial root growth*

In most cases, root length density (RLD) declined linearly with soil depth to 40 cm depth at 41 DAW (mid-pod-filling stage) in 1991 (Fig. 4). In N0, short-term waterlogging increased RLD in the 0–10 cm soil layer (3.17 ± 0.99 versus 2.46 ± 0.37 km m^{-3} for the

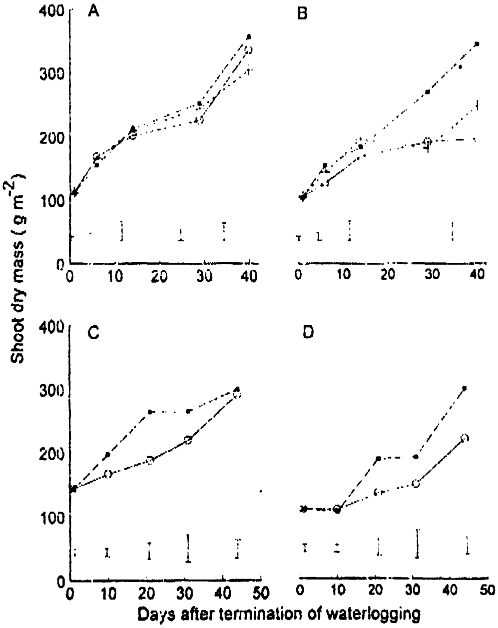

Fig. 3. Effect of N top-dressing on shoot mass after waterlogging in 1991 (A: control, B: waterlogging) and 1992 (C: control, D: waterlogging). N0 (○), N1 (■) and N2 (+) treatments. Vertical bars are standard errors of means for the comparisons at any treatment combination.

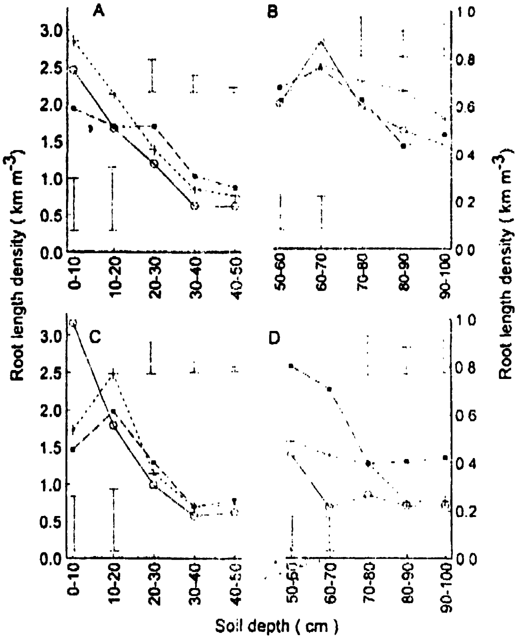

Fig. 4. Effect of N top-dressing on root length density in various soil layers at 41 days after termination of waterlogging in 1991. Control (A, B) and waterlogged plants (C, D). N0 (○), N1 (■) and N2 (+) treatments. Vertical bars are standard errors of means for the comparisons at any treatment combination.

mean ± standard error of waterlogged and control, respectively), but decreased considerably in the soil layer 50–100 cm (0.33 ± 0.03 versus 0.61 ± 0.14 km m^{-3} for waterlogged and control, respectively). Consequently the root distribution of waterlogged pigeonpea became shallow without N top-dressing. Top-dressing of N did not affect RLD significantly in both 0–50 cm and 50–100 cm soil layers for control plants (Fig. 4A and 4B). Meanwhile, the effect of N top-dressing on RLD of waterlogged plants was evident in the 50–100 cm soil layer (Fig. 4D). The increase in RLD was more evident in N1 than in N2, although both were considerably smaller than in the 0–10 cm soil layer for control plants (Fig. 4C).

The observations of root profiles were carried out three times in 1992 for each of the four treatments to examine seasonal changes in more detail (Fig. 5). Increase in RLD of control plants without N top-dressing was confined mainly to the 0–30 cm soil layer from 1 to 12 DAW and then extended to deeper layer (0–60 cm) (Fig. 5A). Top-dressing of N enhanced root growth of control plants in the 0–20 cm soil layer from 1 to 12 DAW (Fig. 5B). However, further increase in RLD of control plants with N top-dressing was not found in those shallow profiles during the next 16 d, but was found in the deeper soil layer (30–90 cm).

Root growth was severely damaged by waterlogging. Average RLD of waterlogged plants was 54% of control plants in the 0–50 cm soil layer, and 44% in the 50–100 cm soil layer at 1 DAW. For the first 12 d after waterlogging, an increase in RLD was restricted to the 0–20 cm soil layer without N top-dressing (Fig. 5C). This increment in the shallow layers continued until 28 DAW, and few roots were found below 50 cm depth. Top-dressing of N enhanced the significant increase in RLD of waterlogged plants in the shallow soil (0–20 cm) during the first 12 d after waterlogging (Fig. 5D). However, a further increase was not found in those shallow layers but there was an increase below 20 cm depth during the next 16 d.

3.4. Nodule activity

Waterlogging did not decrease total nodule activity (TNA) at 14 DAW in 1991 (Table 1). However, TNA

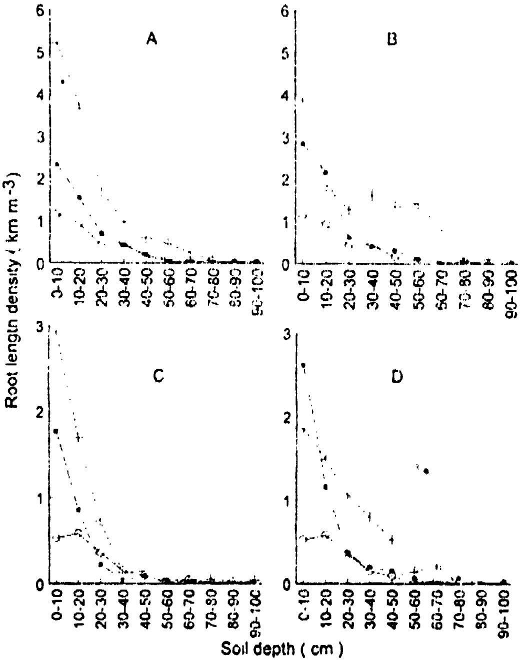

Fig. 5. Seasonal change in root length density in various soil layers after waterlogging in 1992. Control at N0 (A) and N1 (B) treatments and waterlogging at N0 (C) and N1 (D) treatments. 1 (○), 12 (■) and 28 (+) days after termination of waterlogging.

Table 1
Effects of N top-dressing on total nodule activity (nmol m^{-2} s^{-1}) after waterlogging

Treatment		1991	1992		
		14 DAW[a]	1 DAW	12 DAW	28 DAW
Control	N0	6.58	6.13	5.76	5.31
	N1	5.79	–	4.57	8.68
	N2	1.35	–	–	–
Waterlogging	N0	5.80	2.04	2.28	2.77
	N1	4.42	–	2.32	5.07
	N2	1.76	–	–	–
	SE(±)[b]	1.09	1.06	0.64	0.84

[a]Days after the termination of waterlogging. [b]Standard errors of means for the comparisons at any treatment combination.

Table 2
Effects of waterlogging and N top-dressing on seed yield

N Treatment	Seed yield (g m^{-2})			
	1991		1992	
	Control	Water	Control	Water
N0	115(100)[a]	75(100)	112(100)	85(100)
N1	122(106)	118(157)	127(113)	121(142)
N2	126(110)	99(132)	–	–
SE(±)[b]		8		7

[a]Figures in parentheses show respective seed yields as a percentage of yield at N0 treatment in the same main treatment (control or waterlogging). [b]Refer Table 1.

did decrease in both control and waterlogged plants, slightly with N1 treatment, and significantly with N2. In 1992, seasonal changes in TNA were measured from 1 DAW to 28 DAW. TNA was kept nearly constant in control plots without N-top dressing. Waterlogging depressed nodule activity much more severely in 1992 than in 1991. TNA of waterlogged plants without N top-dressing was 33, 40 and 52% of the control at 1, 12 and 28 DAW, respectively. The N1 treatment slightly decreased TNA at 12 DAW, but increased TNA of both control and waterlogged plants at 28 DAW. TNA of waterlogged plants with 50 kg N ha^{-1} reached 95% of the control without N top-dressing at 28 DAW.

3.5. *Seed yield*

Grain yield was decreased considerably by waterlogging without N top-dressing. The reduction was 35% in 1991 and 24% in 1992 compared with the control at the N0 level (Table 2). However, the yield difference between control and waterlogged plants became much smaller with N top-dressing due to greater N response of waterlogged plants. The yield reduction in N1 was only 3% in 1990 and 5% in 1991, as compared with the control.

4. Discussion

Short-duration pigeonpea was severely damaged by short-term waterlogging, resulting in yellowing of the whole canopy followed by senescence and abscission of lower leaves. The symptom is attributable to N shortage (Nathanson et al., 1984; Sugimoto et al., 1988b; Matsunaga et al., 1992). Slight iron chlorosis might have also occurred in the young upper leaves simultaneously, but could not be distinguished by visual observation. In control plots no symptom of iron chlorosis occurred throughout the growing season. Nitrogen top-dressing compensated for impaired shoot growth completely or partially. The leaf chlorophyll and shoot dry mass of waterlogged plants were 78 and 84% (average of two years), respectively, of control plants immediately after waterlogging, but recovered to 92 and 98% of the control at the pod-filling stage with top-dressing of 50 kg N ha^{-1}. Adequate soil moisture after waterlogging should assure the N response of pigeonpea on Vertisols (Burford et al., 1989).

Few studies have reported the effect of waterlogging on the spatial root distribution in field-grown leguminous crops (Cannell et al., 1985). Short-term waterlogging decreased root length density to nearly 50% of the control in both shallow and deep soil layers immediately after waterlogging (1 DAW). During the subsequent recovery period the roots grew mainly in the shallow soil layers. Consequently, the distribution of roots of waterlogged plants became more shallow. The rapid formation of new adventitious roots that was observed near the soil surface in short-duration pigeonpea after waterlogging (Matsunaga et al., 1992) should allow waterlogged pigeonpea to uptake top-dressed N efficiently. We observed that short-duration pigeonpea in the control plots also failed to develop roots in the deep soil layer (below 70 cm) by the mid-pod-filling stage in 1992, when it rained frequently in early August (43 to 58 d after sowing). The rainfall during this period reached 239 mm, accounting for 30% of average annual rainfall (760 mm) at this location.

Control plants developed deeper roots in 1991 than in 1992. Root growth did not respond to N top-dressing. In contrast, root development of waterlogged plants was improved in the deep soil layers by N top-dressing. Subsequent observations of root growth in 1992 revealed the effect of N top-dressing in more detail. N top-dressing enhanced root growth considerably in the shallow soil layer (0–20 cm) for the first 11 d after application, while the response shifted to the deeper soil layer over the next 16 d. A similar effect of N top-dressing on root development was observed in control plants, probably due to poor root development in the deep soil layer in 1992.

Short-duration pigeonpea is infrequently subjected to terminal drought stress after the monsoon season in peninsular India (Johansen et al., 1989), but can still suffer from terminal drought in October if root development is limited at depth. A deep root system is considered important in adaptation to semi-arid regions (Arihara et al., 1991). Soybean is reported to be more susceptible to water deficit after transient waterlogging (Sugimoto et al., 1988b). Therefore, partial recovery of the root system in the deep soil layer by N top-dressing could be important in minimizing the reduction in seed yield due to the drought after waterlogging.

Total nodule activity (TNA) in short-duration pigeonpea was decreased by short-term waterlogging. Symbiotic nitrogen fixation is more sensitive to excess water than other plant processes in leguminous crops (Ae and Nishi, 1983; Smith, 1987). In 1992 top-dressing with 50 kg N ha^{-1} increased TNA one month later. The increase in nodule activity is a consequence of enhanced shoot growth or vice versa. Sugimoto et al. (1989) reported increased nodule activity of waterlogged soybean by enhancement of shoot growth after foliar application of urea. Greater nodule activity is associated with larger shoot growth (Matsunaga and Matsumoto, 1986).

Seed yield was considerably reduced in short-duration pigeonpea by short-term waterlogging. However, the reduction in seed yield was alleviated by N top-dressing, which could be attributed to increased nodule activity and quicker recovery of shoot and root growth from waterlogging damage. However, compared with 50 kg N ha^{-1}, the application of 100 kg N ha^{-1} was less effective in alleviating waterlogging damage, due to smaller recovery of shoot and root growth, and severe depression of nodule activity in the reproductive growth stage. It is important for maximizing seed yield to keep the nodule activity high for as long as possible in leguminous crops (Lawn and Brun, 1974; Troedson et al., 1989a, b). Consequently the dosage of top-dressing should be sufficient to increase shoot and root growth of waterlogged plants, but not so large as to affect nodule activity strongly. A suitable dosage determined in this study was 50 kg N ha^{-1}.

It is important to develop new varieties which can tolerate waterlogging because chemical fertilizer is used infrequently in upland crops in India (Burford et al., 1989). Chauhan (1987) found some genetic difference in waterlogging tolerance in pigeonpea, suggesting the possibility of successful development of new varieties. However, this work has not been completed. In the present study N top-dressing to pigeonpea damaged by waterlogging proved to be reliable in alleviating the yield reduction due to waterlogging damage on Vertisols because water content was sufficient to allow active formation of new adventitious roots in the shallow soil soon after waterlogging and therefore uptake of applied nitrogen fertilizer, leading to quick recovery of shoot and root growth. Therefore, the N fertilizer top-dressing should be seriously considered an alternative technology for yield maintenance until new varieties are available.

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