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Resources use efficiency of field grown transplanted rice (*Oryza sativa* L.) under irrigated semiarid environment

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Abstract

Resources use efficiency of rice crop was studied under irrigated semiarid conditions. Two field experiments were conducted at the Experimental Farm, University of Agriculture, Faisalabad (UAF), Pakistan (latitude 31º25´N, longitude 73º09´E, and altitude 184.4 m from sea level), for two years. Variables in the study include viz. three population densities, five nitrogen fertilizer rates in the first experiment and similarly three population densities and five irrigation regimes in the second experiment. For these resources, radiation interception and radiation conversion efficiency (RCE = ε), water use and water use efficiency (WUE = w), agronomic nitrogen use efficiency (ANUE = an) and economic nitrogen use efficiency (ENUE = en) were estimated. Relationships were also studied among various resources. Particularly RCE (ε) and WUE (w) were estimated by two approaches. The results revealed in experiment that cumulative intercepted photosynthetically active radiation (CIPAR) varied from 990 to 1016 MJ m^{-2} in various nitrogen fertilizer levels. Plant density did not affect significantly RCE in both the seasons and it ranged from 1.26 to 1.28 g MJ^{-1} among different densities. Averaged over the two years data mean RCE for cumulative above-ground total dry matter (CATDM) ranged from 1.15 to 1.36 g MJ^{-1} among different fertilizer levels. The results depicted in Experiment 2 revealed that increasing density from one seedling $hill^{-1}$ to three seedlings $hill^{-1}$ significantly increased the CIPAR. Averaged over the two years data of RCE ranged from 1.41 to 1.44 g MJ^{-1}. Increasing application of irrigation significantly and linearly enhanced RCE for CATDM ranging from 1.34 to 1.49 g MJ^{-1}. Overall cumulative crop evapotranspiration (CCET) varied from 540 to 575 mm among different densities. Similarly CCET varied from 464 to 632 mm among different irrigation regimes. WUE varied from 23.1 to 23.7 kg ha^{-1} mm^{-1} among different densities. Averaged over the two seasons WUE for CATDM decreased with increasing application of irrigation and ranged from 25.2 to 21.9 kg ha^{-1} mm^{-1}. The relationships between CATDM production and cumulative leaf area duration (CLAD) and CIPAR in Experiment 1 and CLAD, CIPAR and CCET in Experiment 2 were linear. Agronomic and economic nitrogen use efficiencies were higher at NF_3 (N 150 kg ha^{-1}).

Key words: *Oryza sativa* L., resources, nitrogen use efficiency, water use efficiency, radiation use efficiency, rice.

Introduction

Stability and growth of all nations in the world in present and future scenarios is only possible by using their resources efficiently and effectively to meet the needs of food security of burgeoning populations. Pivotal role of agriculture is to ensure cyclic supply of food commodities without having adverse effect on environment [5]. In Pakistan, rice holds second pitch after wheat in terms of production and consumption. Rice production constitutes the major economic activity and a key source of employment for rural population of Pakistan [12]. It is being grown on an area of 2515 thousands hectares with an annual production of 5563 thousand tons of grains and having average yield of 2211 kg ha^{-1} [9].

Water availability is critical for agricultural production [20] and now'adays water is diminishing day by day even under irrigated agriculture scenario in the world and particularly in Pakistan. Lowland rice fields have relatively high water requirements and their sustainability is threatened by increasing water scarcity[15]. Rice crop is an important target for reductions in water use because of its large water requirement compared with that of other crops. Water stress affects crop phenology and leaf area development, ultimately resulting in low yield [32]. The quantity of irrigation water needed for the crop depends upon climate, crop and soil characteristics [4]. However, the amount of water requirement can be altered by changing the irrigation schedule and method of crop establishment [30]. Lack of proper water management is probably one of the most constraints to greater rice yield [38]. After water the most crucial one is the nitrogen. Nitrogen, being an integral part of structural and functional proteins, chlorophyll and nucleic acid, plays a vital role in crop development [46]. The main reasons for N deficiency include high cropping intensity, failure of sowing of leguminous crops in existing cropping patterns and other losses such as runoff, denitrification and volatilization and last but not least low use of nitrogenous fertilizers due to their unavailability as well as black-marketing. Our main center of attention in this study was to determine the relationships between different resources, viz., (i) cumulative above-ground total dry matter (CATDM) and cumulative intercepted photosynthetically active radiation (CIPAR) for radiation conversion efficiency (RCE) (ε; g MJ^{-1}), (ii) CATDM and cumulative crop evapotranspiration (CCET) for water use efficiency (WUE) (w; g m^{-2} mm^{-1}), (iii) RCE and agronomic nitrogen use efficiency (ANUE) and (iv) RCE and WUE to find out the optimum combinations of existing resources for the maximum harvesting of the natural and man controlled resources for enhanced crop productivity and finally to handle food security. Results from the referenced data revealed that resources use efficiencies (ε and w) were found to be constants during the growing seasons of the crops for a given set of environmental conditions and species [22, 25, 35, 44]. However, the differential response for these two resources may occur under different cropping systems, among species [6]. To best of our knowledge, no research has been conducted employing simultaneous relationship studies regarding field-grown rice under irrigated semi-arid conditions. The present study was therefore designed to study resources use efficiencies of transplanted rice under irrigated semi-arid environment.

Materials and Methods

***Field experiments*:** Field experiments were conducted on fine aromatic rice cultivar (Basmati-385) at the Experimental Farm, University of Agriculture, Faisalabad (UAF), Pakistan (latitude 31º25´N, longitude 73º09´E and altitude 184.4 m from sea level). The soil belongs to Lyallpur series (aridisol-fine-silty, mixed, hyperthermic Ustalfic, hap-larged in USDA classification and Haplic Yermosols in FAO classification. The pH of experimental site varies from 7.80 to 7.90 and organic matter from 0.73 to 0.76%. The climate of the area is semi-arid with an average annual temperature of 27ºC and average annual rainfall of 1000 mm. The weather regime during the course of experimentation is given in Table 1. Experiment 1 included the following treatments, three plant densities, viz., PD$_1$ 16, PD$_2$ 32 and PD$_3$ 48 plants m^{-2} and five nitrogen fertilizer regimes, viz., NF$_0$ control, NF$_1$50, NF$_2$ 100, NF$_3$ 150 and NF$_4$ 200 kg ha^{-1}. The treatments included in Experiment 2 were three plant densities, viz., one seedling hill^{-1}, two seedlings hill^{-1} and three seedlings hill^{-1} along with five irrigation regimes, viz., I$_1$ 62.5, I$_2$ 77.5, I$_3$ 92.5, I$_4$ 107.5 and I$_5$ 122.5 cm. A randomized complete block design was used with three replications. Plot size was 2.0 m × 3.0 m and there were 8 rows plot^{-1} and 12 plants row^{-1}. The mean seedling age of rice at transplanting was about 1 month. Seedlings were transplanted manually in a puddled field in standing water at 22.5 cm × 22.5 cm plant-to-plant and row-to-row distance in both years and experiments. All the P and K and half of the nitrogen fertilizer in the form of single super phosphate (SSP), potassium sulphate and urea, respectively, were applied to each plot at the time of puddling before transplanting except the control treatment. The remaining dose of nitrogen as per treatment in Experiment 1 and standard dose in Experiment 2 was applied at the tillering stage. Zinc was applied @25 kg ha^{-1} ten days after transplanting during both years and experiments. A total of 16 irrigations were applied to each treatment in Experiment 1 and as per treatments in Experiment 2. Rice was harvested manually close to ground level with sickles. All other agronomic practices such as weeding, plant protection measures, etc., were standard and uniform for all the treatments.

Table 1. Monthly mean weather conditions during crop growth season (July-Oct).

Month	Temperature (ºC)	Rainfall (mm)	Solar radiation (MJ m^{-2} d^{-1})	Relative humidity (%)
7	32.23	8.08	19.81	66.88
8	32.53	6.03	23.96	59.63
9	29.67	3.95	22.74	58.91
10	27.69	0.00	20.06	52.77

Source: Depart. of Crop Physiology, University of Agriculture, Faisalabad, Pakistan.

Sampling protocols: Total seven harvests including final harvest were made twice in a month in each season. A randomly selected area of 45 cm × 45 cm was harvested from each plot avoiding border effect. The plants were divided into leaves, stem and grains (when present). Fresh weights were recorded separately. Sub-samples of 100-200 g of green leaves and branches were oven-dried to a constant weight at 80ºC for determining the dry weight. A sub-sample of 50-100 g of green leaves was taken and leaf area was measured with an electronic area meter (Licor, model 3100). The leaf area index (LAI) was calculated as the ratio of total leaf area to land area [48].

Estimation of intercepted photosynthetically active radiation (IPAR): Daily total incident solar radiation (ISR) was determined using Ångström's equation [8]:
$SR = [SR_0 (a + b\ n/N)]$ (MJm^{-2}day^{-1}), where SR$_0$ is the extraterrestrial radiation, *N* the maximum possible sunshine duration, *n* is measured sunshine duration and *a* and *b* are constants. The values of *a* and *b* were used as recommended by Allen and co-workers [7], for those areas where data for SR is not available. The data for n was obtained from observatory of Department of Crop Physiology (CP), University of Agriculture, Faisalabad (UAF) (Table 1).

The fraction of intercepted radiation (Fi) was estimated from LAI using the exponential attenuation equation suggested by Monteith and Elston [34] and also used by other scientists [11, 28, 47, 49]:
$Fi = [1- \exp(-K \times LAI)]$, where K is extinction coefficient for total solar radiation [33]. The coefficient is equal to 0.306. The PAR was calculated by multiplying 0.5 to the total incident radiation [36, 43, 45]. Multiplying these totals by the appropriate estimates of Fi gave an estimate of the amount of radiation intercepted (Sa) by a crop canopy as suggested by some scientists [11, 43]. $Sa = [Fi \times Si]$, where, Si is the total amount of incident PAR.

Radiation conversion efficiency (RCE): The radiation conversion efficiency (RCE) for CATDM was defined by Monteith [33] and also used by many scientists [27-29, 47] was calculated by the following formula: $RCE_{CATDM} = [CATDM\ (g\ MJ^{-1})]/CIPAR\ (\Sigma Sa)$.

Estimation of water use: Actual cumulative crop evapotranspiration (CCET) was estimated by multiplying potential evapotranspiration (PET) with appropriate value of a crop coefficient, which usually corresponds closely with the green crop cover as suggested by Doorenboss and Pruitt [11]. Daily Penman's PET was calculated by using standard programme of [CROPWAT] developed by FAO [12] and also used by other workers [10, 24, 39].

Water use efficiency (WUE): Water use efficiency (WUE) was calculated as CATDM produced per unit crop water used. WUE for CATDM was calculated by the following formula:

WUE_{CATDM} = [CATDM (kg $ha^{-1}mm^{-1}$)]/CCET (ΣET).

Agronomic nitrogen use efficiency (ANUE): Nitrogen use efficiency (NUE) has been variously defined depending on the context in which it is used [37, 50]. Barber's definition of efficiency [the amount of increase in yield of the harvested portion of crop per unit of fertilizer nutrient applied] reflects agronomists' conception of the term and is also referred as grain to nutrient ratio. ANUE was calculated as grain yield produced per rate of nitrogen applied [37, 50]:

$ANUE_{GY} = [GY_{(F)} - GY_{(C)}$ kg kg^{-1}]/Rate of N applied.

Economic nitrogen use efficiency (ENUE): Economic nitrogen use efficiency (ENUE) or value cost ratio (VCR), defined by economists in terms of rupees returned for each rupee spent on nitrogen and being most relevant to the farmer for making financial decisions, was calculated as suggested by scientists [37], [50]:

VCR = [value of CATDM $(_F)$ – value of CATDM $(_C)$]/ Value of N fertilizer applied.

Statistical methods: The data were statistically analyzed using MSTATC software [21]. Analysis of variance techniques were employed to test the overall significance of the data, whilst differences between treatment means were compared using the least significant difference (LSD) test at $P \leq 0.5$ [42].

Results and Discussion

Experiment 1 (population and nitrogen dynamics)

Rice crop seasonal growth: Seasonal rice crop growth was determined by using the effective leaf area (green only), leaf area duration and above-ground biomass production throughout the crop season. Leaf area index (LAI) increased steadily during the initial stage of canopy establishment, reaching the maximum value of 7.54. During these developmental stages the maximum LAI was obtained on 12-15 Sep (70-74 DAT) for both years. Thereafter it declined slowly until 27 Sep (85 DAT) and then it declined sharply during grain filling stage (GFS) until final harvest 25-27 Oct (110-112 DAT) during both the seasons. Differences in LAI among nitrogen fertilizer treatments were significant throughout the season in both the years. Increasing rates of nitrogen fertilizer until (NF_4) significantly increased LAI compared to NF_0 or lower rates of nitrogen fertilizer. Similarly NF_3 (150 kg ha^{-1}) increased LAI accumulation over NF_0, NF_1 and NF_2, whereas both NF_3 and NF_4 rates of application were statistically at par for LAI. At higher rates of NF application, leaf senescence was later as compared to lower or control treatment. All N levels increased the growth of rice during vegetative and reproductive phases compared to control. These results are in line with the findings of Cheyglinted and co-workers [16]. As a consequence of difference in LAI and leaf senescence behavior, CLAD ranged from 266 to 336 days for control NF_0 and NF_4, respectively. ATDM was higher at higher rates of nitrogen fertilizers (NF_3 and NF_4) as compared to control (NF_0) and lower rates of application (NF_1 and NF_2). Relationship between CATDM accumulation and CLAD was significant and common regression accounted for (97%) of the variation (Fig. 1), indicating that 4.66 g m^{-2} day^{-1} of ATDM was produced.

Radiation use and radiation conversion efficiency (RCE): Total incident PAR was 1958 MJ m^{-2} in Season I and 1974 MJ m^{-2} in Season II, out of which about 52.8 and 45.2% were intercepted. A plant density of 32 plants m^{-2} (PD_2) intercepted more PAR than PD_1, while differences in the CIPAR between PD_2 and PD_3 densities were non-significant (Table 2). CATDM was plotted against CIPAR for all the treatments, which was linearly correlated for rice crop during the entire crop season. Increasing rates of NF application highly, significantly and linearly increased the CIPAR over control (NF_0) or lower rates of application (NF_1 and NF_2). Averaged over the two years, CIPAR varied from 909 to 1016 MJ m^{-2} in NF_0 and NF_4, respectively (Table 2). In both seasons plant density did not affect significantly RCE, which ranged from 1.26 to 1.28 g MJ^{-1} among different densities. Increasing rates of NF application significantly increased RCE over control or lower rates of application in both the seasons. Differences in RCE between NF_3 and NF_4 were, however, non-significant. Averaged over two years data mean RCE for CATDM ranged from 1.15 to 1.36 g MJ^{-1} among different fertilizer levels (Table 2). This is because higher N supply probably promotes higher leaf N concentration that enhanced rate of photosynthesis and RCE. These results corroborate the findings of Hasegawa and Horie [23]. This study demonstrated a linear relationship between CATDM and CIPAR (Fig. 2), and regression gave a slope of 3.18 g produced for each MJ of CIPAR. The relationship between grain yield and CIPAR was also linear [1]. However, Kiniry and co-workers [21] reported RCE of 2.2 g MJ^{-1} of intercepted PAR for a non-stressed rice crop. The increased rates of NF application increased biomass production and photosynthetic capacity per unit of intercepted solar radiation (ISR) in rice as already mentioned by Albrizio and Steduto [6] for some other field grown crops.

Table 2. Cumulative above-ground total dry matter production, cumulative IPAR, radiation conversion efficiency and cumulative LAD as affected by population density and nitrogen levels.

Treatment	CATDM (g m^{-2})	CIPAR (MJ m^{-2})	RCE_{CATDM} (g MJ^{-1})	CLAD (days)
		Population density		
PD_1	1.18	950.11	1.26	291
PD_2	1.24	982.77	1.28	317
PD_3	1.22	966.84	1.27	303
LSD 5%	0.06	28.43	0.03	20.26
Significance	**	*	NS	*
Linear	**	NS	NS	NS
Quadratic	**	*	NS	NS
		Nitrogen fertilizer application		
NF_0	1.03	908.54	1.15	267
NF_1	1.12	939.12	1.21	284
NF_2	1.23	972.11	1.28	305
NF_3	1.33	997.37	1.35	324
NF_4	1.37	1015.73	1.36	338
LSD 5%	0.08	36.71	0.04	26.16
Significance	**	**	**	**
Linear	**	**	**	**
Quadratic	**	NS	NS	NS
Cubic	**	NS	NS	NS

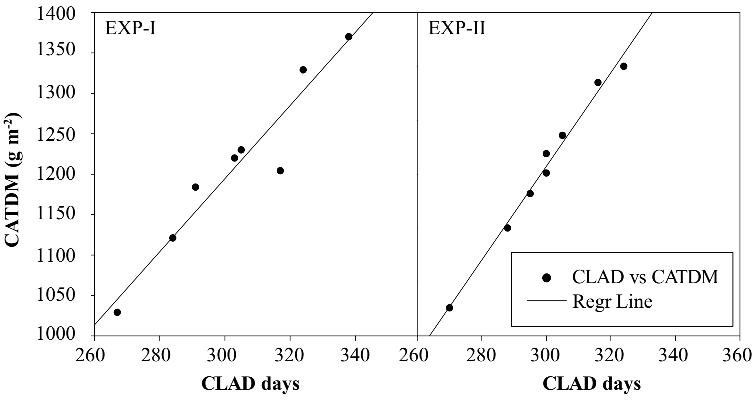

Figure 1. Relationship between cumulative above-ground total dry matter (CATDM) and cumulative leaf area duration (CLAD) in both experiments.

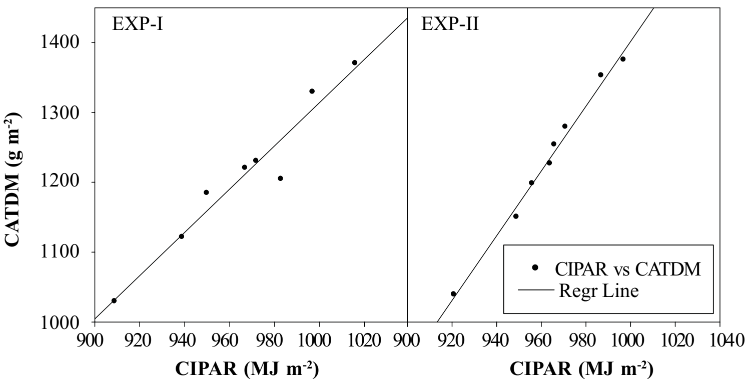

Figure 2. Relationship between cumulative above-ground total dry matter (CATDM) and cumulative intercepted photo-synthetically active radiation (CIPAR) in both experiments.

Table 3. Agronomic and economic nitrogen use efficiencies as affected by nitrogen rates in rice crop.

Treatment N kg ha^{-1}	ANUE (kg kg^{-1})	ENUE
	Nitrogen fertilizer application	
NF_0 = 0	-	-
NF_1 = 50	6.00	3.72
NF_2 = 100	6.50	4.16
NF_3 = 150	8.53	5.46
NF_4 = 200	7.65	4.87

Agronomic nitrogen use efficiency (ANUE): For the rice crop ANUE varied from 6.00 to 8.53 kg kg^{-1} among nitrogen fertilizer levels (Table 3). ANUE increased linearly up to 150 kg ha^{-1} and then decreased at higher rate of 200 kg ha^{-1} included in this research. Our results are in line with the findings of others [26].

Economic nitrogen use efficiency (ENUE): ENUE varied from 3.72 to 5.46 among various nitrogen fertilizer rates (Table 3). Trend was similar as in the case of ANUE. From economic point of view NF_3 (150 kg ha^{-1}) is the most appropriate one to be used at farmers level as well.

Experiment 2 (population and irrigation regimes)

Rice crop seasonal growth: Similarly as in Experiment 1 (population and nitrogen dynamics) seasonal rice crop growth was determined by using the effective leaf area (green only), CLAD and ATDM production during both crop seasons. LAI increased steadily during the initial stage of canopy establishment, reaching the maximum value of 7.29. During the different developmental stages, the maximum LAI was obtained on 20 Sep (78 DAT) for both the seasons. Thereafter, it declined slowly until 25 Sep (83 DAT), and then it declined sharply during GFS until final harvest on 26 Oct (111 DAT) during both the seasons. Differences in LAI were significant among densities. Averaged over the two years data, the maximum LAI (6.91) was observed in case of two seedlings hill^{-1}. Increasing application of I_1 to I_5 significantly and linearly increased LAI in both the seasons. However, the differences between I_4 and I_5 were non-significant. Increasing rate of irrigation (I_5) significantly increased LAI compared to I_1 or lower rates of irrigation application (I_2 and I_3). At higher regimes of irrigation application, leaf senescence was delayed as compared to lower levels of irrigation. As a consequence of difference in LAI and leaf senescence behavior, CLAD ranged from 270 to 324 days for I_1 and I_5, respectively. Final ATDM accumulation varied from 1225.56 in I_1 to 1449.78 g m^{-2} in I_5. CATDM was linearly related with CLAD (Fig. 1) and the common regression line accounted 98% of the variance in the data, indicating that 4.35 g m^{-2} day^{-1} of ATDM was produced.

Radiation use and radiation conversion efficiency (RCE): Total incident PAR was 1958 MJ m^{-2} in Season I and 1974 MJ m^{-2} in Season II, out of which about 52.8 and 45.2% were intercepted. A plant density of two seedlings hill^{-1} intercepted more radiation (F_i). In both seasons two and three seedlings hill^{-1} enhanced Fi until 42 DAT, thereafter, all the densities showed non-significant differences in Fi until 98 DAT. Maximum Fi values were reached at 70 DAT in both the seasons. Table 4 presents the effects of treatments on CIPAR. Increasing density from one seedling hill^{-1} to three seedlings hill^{-1} significantly increased the amount of CIPAR. However, difference in CIPAR between two and three seedlings hill^{-1} was non-significant. Averaged over the two seasons, CIPAR was 956, 971 and 964 MJ m^{-2} in one, two and three seedlings, respectively (Table 4). Increasing irrigation application from I_1 to I_5 significantly and linearly increased the amount of CIPAR. CIPAR difference between I_4 and I_5 irrigation regimes was non-significant. Averaged over the two years data CIPAR was 921, 949, 966, 987 and 997 MJ m^{-2} in I_1, I_2, I_3, I_4 and I_5, respectively. Table 4 also presents the effect of treatments on RCE for CATDM. In both seasons plant density did not affect significantly RCE for CATDM. Averaged over the two years data RCE ranged from 1.41 to 1.44 g MJ^{-1}. Increasing application of irrigation significantly and linearly enhanced RCE for CATDM ranging from 1.34 to 1.46 g MJ^{-1} (Table 4). Seasonal and final ATDM was positively and linearly related with the CIPAR during both the seasons. This study demonstrated a positive and linear relationship between CATDM and CIPAR (Fig. 2) and regression gave a slope of 3.11 g produced for each MJ of CIPAR.

Table 4. Cumulative above-ground total dry matter production (CATDM), cumulative IPAR, radiation conversion efficiency (RCE), cumulative crop ET, water use efficiency (WUE) and cumulative LAD as affected by population density and irrigation regimes.

Treatment	CATDM ($g\ m^{-2}$)	CIPAR ($MJ\ m^{-2}$)	RCE_{CATDM} ($g\ MJ^{-1}$)	CCET (mm)	WUE ($kg\ ha^{-1}\ mm^{-1}$)	CLAD (days)
			Population density			
PD_1	1.33	956.15	1.41	539.82	23.70	295
PD_2	1.38	971.11	1.44	575.46	23.10	305
PD_3	1.35	964.19	1.41	559.10	23.10	300
LSD 5%	0.03	11.25	0.02	23.73	0.06	7.48
Significance	**	*	*	*	NS	*
Linear	NS	NS	NS	NS	NS	NS
Quadratic	**	*	*	NS	NS	*
			Irrigation regimes			
I_1	1.23	921.05	1.34	463.90	25.20	270
I_2	1.30	948.62	1.38	522.99	23.70	288
I_3	1.37	966.06	1.43	562.59	23.20	300
I_4	1.44	986.70	1.46	608.87	22.50	316
I_5	1.45	996.66	1.46	632.27	21.90	324
LSD 5%	0.04	14.52	0.03	30.63	0.07	9.65
Significance	**	**	**	**	**	**
Linear	**	**	**	**	**	**
Quadratic	NS	NS	*	NS	NS	NS
Cubic	NS	NS	NS	NS	NS	NS

Water use and water use efficiency (WUE): Table 4 presents the effect of plant density on seasonal cumulative crop evapotranspiration (CCET). Averaged over the two years data two and three seedlings hill^{-1} significantly increased CCET over one seedling hill^{-1}. Differences in CCET between two and three seedlings hill^{-1} were statistically non-significant. Increasing levels of irrigation application significantly increased CCET. CCET for I_4 and I_5 treatments were statistically at par. The I_3 treatment also increased the CCET over I_1 and I_2 treatments. Overall CCET varied from 540 to 575 mm among different densities. Similarly CCET varied from 464 to 632 mm among different irrigation levels. Table 4 also presents the effect of treatments on WUE for CATDM. Plant density did not affect significantly WUE for CATDM. Averaged over the two seasons WUE varied from 23.1 to 23.7 kg ha^{-1} mm^{-1} among different densities. Increasing application of irrigation significantly decreased WUE for CATDM. Averaged over the two seasons WUE for CATDM decreased with increasing application of irrigation and ranged from 25.2 to 21.9 kg ha^{-1} mm^{-1}. This study demonstrated a positive and linear relationship between CATDM and CCET (Fig. 3) and regression accounted for 99% variance in the data indicating 1.39 g of dry matter was produced mm^{-1} of crop ET. The relationship between grain yield and CCET was also linear [2,4].

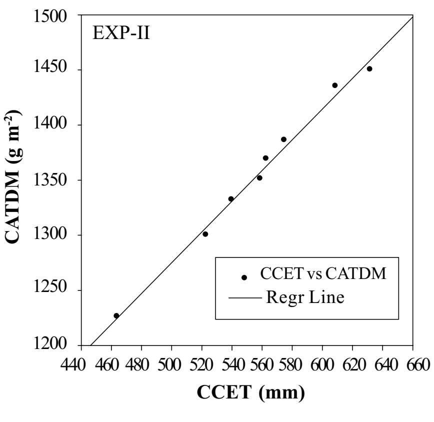

Figure 3. Relationship between cumulative above-ground total dry matter and cumulative crop ET.

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