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MATHEMATICS, ENGINEERING, AND AGRICULTURE

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Engineering is the design of components into a system to adequately serve a need with minimum expenditure of energy and materials. Although increased rice production is a pressing need to meet the increased human energy requirements of Asia, an overall decrease in human energy used in rice production is also necessary if the rice is to be sold at a price acceptable to the consumer and be profitable to the grower. Applied scientific research should fill the gaps in our knowledge of rice production. Agronomic and engineering design techniques may then be used to apply the knowledge. In the absence of integrated knowledge, agronomists, engineers, and farmers must rely on ART rather than SCIENCE. The results are low production and high cost due to a shortage of talented practicing artists (good farmers). This shortage is due to the difficulty of learning the necessary operations which are not expressed explicitly or quantitatively.

Engineering design and economic and engineering systems analysis should be combined with the applied biology of the agronomists to make the best use of the present climate, land, labor, capital, and material resources of the rice farmer. At the same time future systems of production that offer maximum production and minimum costs must be explored. These systems can best be explored if the research information is expressed in quantitative numbers and mathematical equations which hold for a wide range and indicate possible limits. For instance, crop yield is zero for zero water use, but water use may not change on a flooded field as crop yield varies from zero to maximum. Crop yields on zero soil depth will approach zero unless grown in a culture solution, but what changes will occur if plowing and fertilizer application methods increase soil depth? Are shallow soils and frequent surface fertilizer applications preferable to a deep soil with a single basal fertilizer application? The merits of deeper soil are not clearly understood as the mixing of infertile subsoil with a fertile topsoil usually results in yield reduction for several crops. Yet, with deep plowing and the addition of fertilizer, the entire soil profile may be improved and brought to a new state of equilibrium. Deeper soils offer a greater reserve or holding capacity for water and nutrients. The management or timeliness of water or fertilizer applications are obviously not as critical in a soil 50 cm deep, as in one only 10 cm deep. However, the relative importance of the various intermediate depths is not as clear.

Experiments have been carried out in which thoroughly mixed Maahas clay was placed on the sloping floors to provide depths of 6 to 40 and 0 to 70 cm. In one experiment the plots were split: one-half fertilized (50 kg of N per ha) and the other not fertilized. The fertilized plots showed a dramatic response in vegetative growth at all soil depths from 0 to 70 cm. However, the grain yield increased in only the 0 to 40 cm depths.

Grain and straw yield increased with increased soil depth in the form of a modified exponential equation of the form, $y = k + ab^x$. However, total

nitrogen recovered from the grain and straw showed a linear trend with a sharp break at a soil depth of 40 cm. (Fig.). The slope of the N regression lines indicate that 32 gm of N were extracted per cu m of soil in the 0 to 40 cm range. From 40 to 70 soil depths the extracted N averaged only 6 gm per cu m of soil. Total soil nitrogen recovered from the straw and grain was apparently the same in both the fertilized and non-fertilized plots. The additional 50 kg of N per ha shifted the regression lines equivalent to a recovery of 40.7 kg of N in the grain and straw. The fertilizer application was thus equivalent to an additional soil depth of 40.7/320 = 12.7 cm. Grain yields of the two plots show a similar shift as if soil depth were increased by the nitrogen. Straw yields, however, show an upward shift due to the added nitrogen. Additional experiments on the interaction between applied N, soil depth, and time and depth of application should be conducted to allow one to predict at what depth and time nitrogen should be added, and to what depth land preparation should incorporate straw and fertilizer to form a deeper profile.

The results to date indicate that yield increases of grain and straw are more pronounced in soils less than 30 cm deep. Fertile soil depths up to 40 cm definitely increase yields. Soil depths of less than 40 cm respond more to fertilizer applications. For uniformly mixed soil less than 40 cm deep, the yield response is almost linear while on deeper soils the modified exponential trend becomes apparent.

Data in Tables 1, 2, and 3 demonstrate the full implications of soil depth. The values of k, a, b, and x of the equation, $y = k + ab^x$, are given as well as the solution of the equation for soil depths representing 90 and 95 per cent of maximum yield k. The value, k, may be due to either solar radiation or a limited supply of N. Native soil nitrogen taken into the plant varied from 21.4 gm to 32 gm per cu m. Thus, Maahas clay supplied the equivalent of 86 to 128 kg N/ha from the top 40 cm of soil. Soil profiles of 40 cm and over may be impracticable because depth limits the movement of men and machines. However, depths up to 30 cm are not a problem. In many areas, animal land preparation has created a plow sole at depths of 10 to 15 cm which will undoubtedly be too shallow for the most efficient utilization of fertilizer, machines, and land in the future. Knowledge of available plant nutrients per unit soil volume and per area is necessary to calculate how to change the soil depth. Research reported to date suffer from two major defects. Greenhouse pot experiments are based on known soil volume and nutrient quantities but not on known area, while field experiments are based on known area but not on known soil volume or nutrient quantities. Assumptions as to area or volume must be replaced by knowledge of area, volume, and native soil nutrients available to plants, if research findings are to be useful in designing a production system.

The soil depth experiment and an experiment initiated to observe the plant's ability to compensate for spacing gave a lead on a possible method to replace assumptions by values measured by the plant or from the plant's reaction. Seven widely different varieties were selected and interspaced hexagonally with one square meter per plant. Approximately 150 plants of each variety were grown in this manner so that each was a replicate. Twenty-five healthy plants (25 replicates) were measured at harvest and the data, summarized in Table 4 and Fig. , indicate that the product of leaf area and growth

period is closely related to yield when soil area and volume are equal. This relationship could be explored further to enable estimates of field production and native soil fertility to be made from both greenhouse experiments and field experiments. Greenhouse pot experiments would have a known volume of soil; the leaf area and water used would be measured weekly to estimate intercepted solar radiation; field experiments would have control plants on pans of known area and depth placed between regularly spaced plants. The ratio of the N extracted by the controls and the field plants should indicate average root depth. Yields versus limited amounts N would also become available on an absolute basis rather than the present added N plus an unknown value called native fertility.

Table 1. Effect of soil depth on yield of Tainan 3. 1964 Wet season (spacing 30 x 30 cm non-fertilized).

Soil Depth cm	Straw Ht. cm	No. of Tillers per m^2	No. of Panicles per m^2	Weight, gm/sq. meter				N Content (gm/sq. m.) [1]		
				Panicle	Straw	Grain	Plant	Straw	Grain	Plant
4	66	58	38	99	64	91	163	.39	1.12	1.51
8	68	68	56	153	129	138	282	.69	1.58	2.27
12	70	83	71	223	152	202	375	.76	2.29	3.05
16	72	110	71	256	206	231	462	1.48	2.70	4.18
20	74	121	77	285	246	258	531	1.62	3.72	5.34
24	77	129	87	340	264	293	604	1.96	3.89	5.85
28	79	141	90	363	310	310	673	2.20	4.42	6.62
32	79	146	82	341	336	299	677	2.53	4.14	6.67
36	80	152	92	383	332	331	715	2.59	5.10	7.69
k	89	175	96	433	539	356	924	4.23	6.46	10.57
a	-24	-129	-53	-339	-468	-272	-763	-4.05	-5.55	-9.48
b	.882	.805	.734	.798	.890	.767	.845	.889	.857	.869
Centimeters soil depth estimated for 90 and 95 percent of maximum value k.										
Y = 0.9k	46	40	28	40	78	35	54	81	60	67
Y = 0.95k	61	53	38	52	102	45	70	122	78	88

[1] Average soil N = 21.4 gm/cu. m. or 86 kg N/ha to 40 cm depth.

Values of coefficients in formula $Y = k + ab^x$; $x = \frac{\text{Soil Depth} - 4}{4}$

Table 2. Effect of soil depth on yield of PI-215936. 1965 dry season. (Spacing 15 x 20 cm, non-fertilized.)

Soil Depth cm	Straw Ht. cm	No. of Tillers per m^2	No. of Panicles per m^2	Weight, gm/m^2			N Content, gm/m^2		
				Straw	Grain	Plant	Straw	Grain	Plant
8	48	88	83	122	122	244	.81	1.47	2.28
14	50	116	116	193	192	382	1.09	2.48	3.57
20	56	149	145	294	284	578	1.57	3.54	5.11
26	60	185	178	405	384	788	2.16	4.98	7.14
32	64	208	187	461	446	906	2.59	5.81	8.40
38	68	232	216	546	575	1121	3.33	7.80	11.13

Average N removed by plant from soil = 29.3 gm/cu. m. or 117 kg N/ha to 40 cm depth.

Table 3. Effect of soil depth on yield of PI 215936. 1965 dry season. (Spacing 15 x 20 cm; non-fertilized (NF) and fertilized (F) 50 kg N/ha.)

Soil Depth	Straw Ht. cm		No. per Sq. M. Tillers		Panicles		Straw		Weight, gm/sq. m. Panicle		Grain		Plant		N Content, gm/sq. m.[1] Straw		Grain		Plant	
cm	NF	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF	F
10	56	66	168	305	151	218	283	605	261	455	229	400	544	1060	1.33	3.42	2.09	3.88	3.42	7.30
20	66	75	259	316	196	221	496	751	406	503	356	442	902	1254	2.49	5.81	3.96	4.97	6.45	10.78
30	76	81	268	337	208	231	653	905	485	533	426	468	1128	1438	4.20	8.05	5.14	6.02	9.34	14.07
40	77	82	274	341	207	233	688	918	553	595	486	522	1241	1513	5.53	9.42	6.40	7.32	11.93	16.72
50	81	83	272	344	209	237	679	915	590	604	518	519	1268	1519	5.92	9.94	7.21	7.35	13.13	17.29
60	81	82	274	349	217	234	745	925	610	622	535	508	1355	1547	6.80	10.21	7.42	7.53	14.22	17.74
70	80	83	281	348	212	245	769	1008	598	675	525	570	1367	1683	6.88	1078	7.35	8.29	14.23	19.07
k	83	83	280	349	214	244	772	956	663	680	552	573	1368	1664	7.66	10.78	7.78	8.12	15.02	18.57
a	-28	-19	-97	-51	-58	-28	-505	-397	-396	-228	-322	-177	-833	-640	-6.75	-7.82	-5.78	-4.54	-12.54	-12.09
b	.539	.333	.373	.513	.4	.693	.515	.401	.661	.759	.608	.717	.532	.649	.697	.576	.65	.626	.605	.577
Centimeters soil depth estimated for 90 and 95 percent of maximum value k																				
Y=0.9k	30	18	22	16	21	14	38	26	53	54	45	44	40	41	70	46	57	47	52	44
Y=0.95k	41	24	30	26	28	33	49	33	70	79	60	65	50	57	(90)	58	73	62	62	57

Average soil N = 32 gm/cu. m. or 128 kg N/ha to 40 cm depth.
Values of coefficients in formula,

$$Y = k + ab^{x}$$

$$x = \frac{\text{Soil Depth} - 10}{10}$$

Table 4. Experiment No. 7 - Physical dimensions and yield components of seven varieties of widely differing growth habits when interspaced hexagonally 1 plant per square meter. (25 plant samples.)

	Taichung Native 1	PI 215936	IR 9-60	BPI-76 non-photo-sensitive	Century Patna 231	81B-25	Chianung 242
Transplanted	May 18	May 18	May 18	May 18	May 18	May 18	May 18
Harvested	Sept. 14	Sept. 15	Sept. 8	Sept. 15	Sept. 15	Oct. 6	Sept. 14
No. of days in the field (from transplanting to harvesting)	120	121	114	135	121	144	120
Panicles per plant	158	70	126	113	46	94	54
Panicle weight, grams/plant	349	166	384	536	134	325	143
Grain and chaff, grams/plant	320	148	353	500	118	300	122
Clean grain, grams/plant	287	133	336	460	98	267	99
Height of plants, H_{max} cm	98	97	71	116	106	159	97
" " " H_{min} cm	56	74	34	90	91	131	76
Radius of tiller, r' cm	75	84	65	105	97	136	83
Dia. of leaf spread above D_a, cm	114	91	128	126	79	91	80
Hill base dia. below D_b, cm	16	12	17	18	12	17	12
Total tillers per plant	172	84	146	121	59	107	75
Plant area* sq cm	10,207	6,504	12,868	12,469	4,902	6,504	5,027
Plant area x No. of days, m^2 x day	122	77	147	168	59	94	60

* πD_a^2 divided by 4

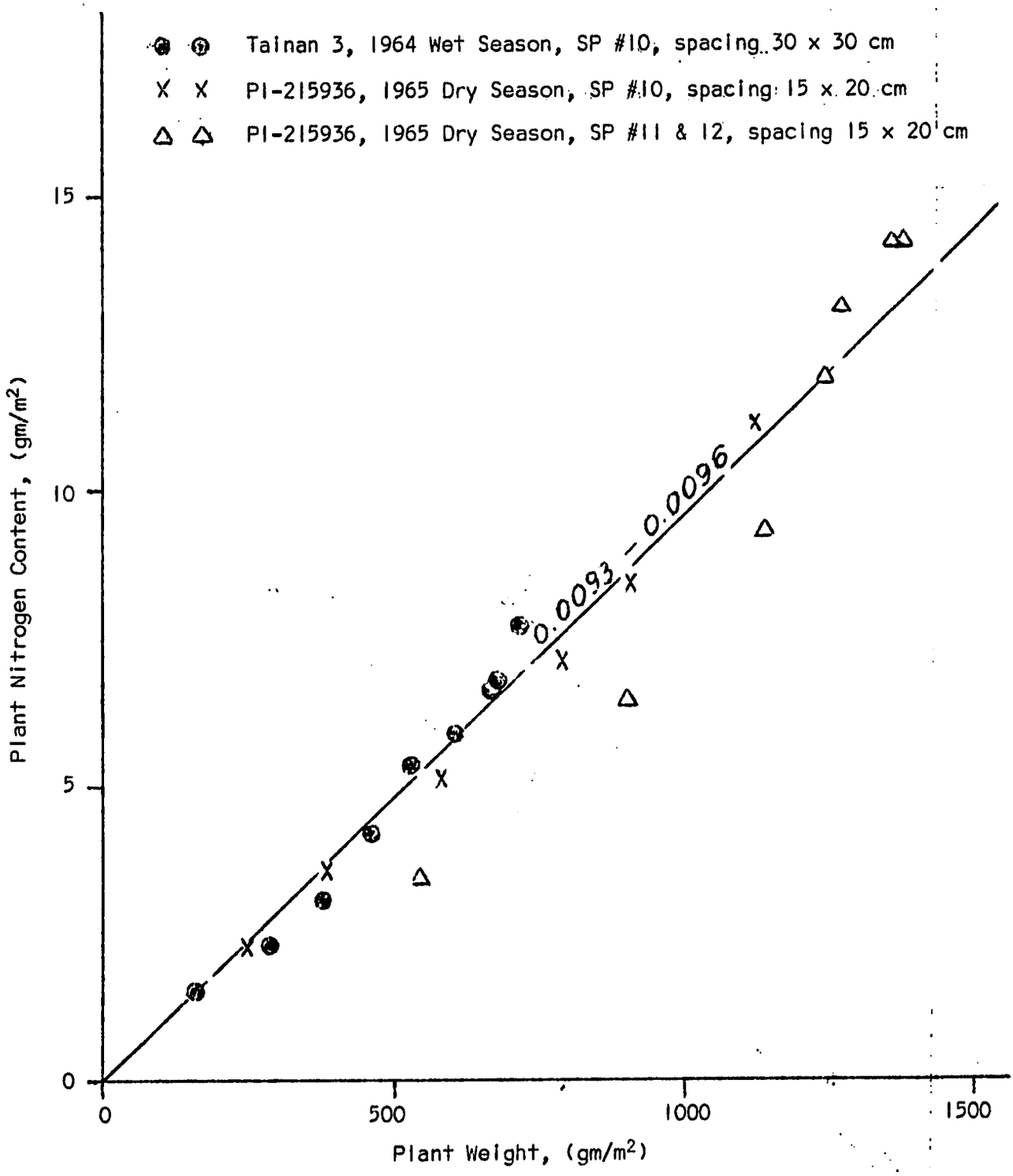

Fig. 5. The effect of plant weight on plant nitrogen content per square meter.

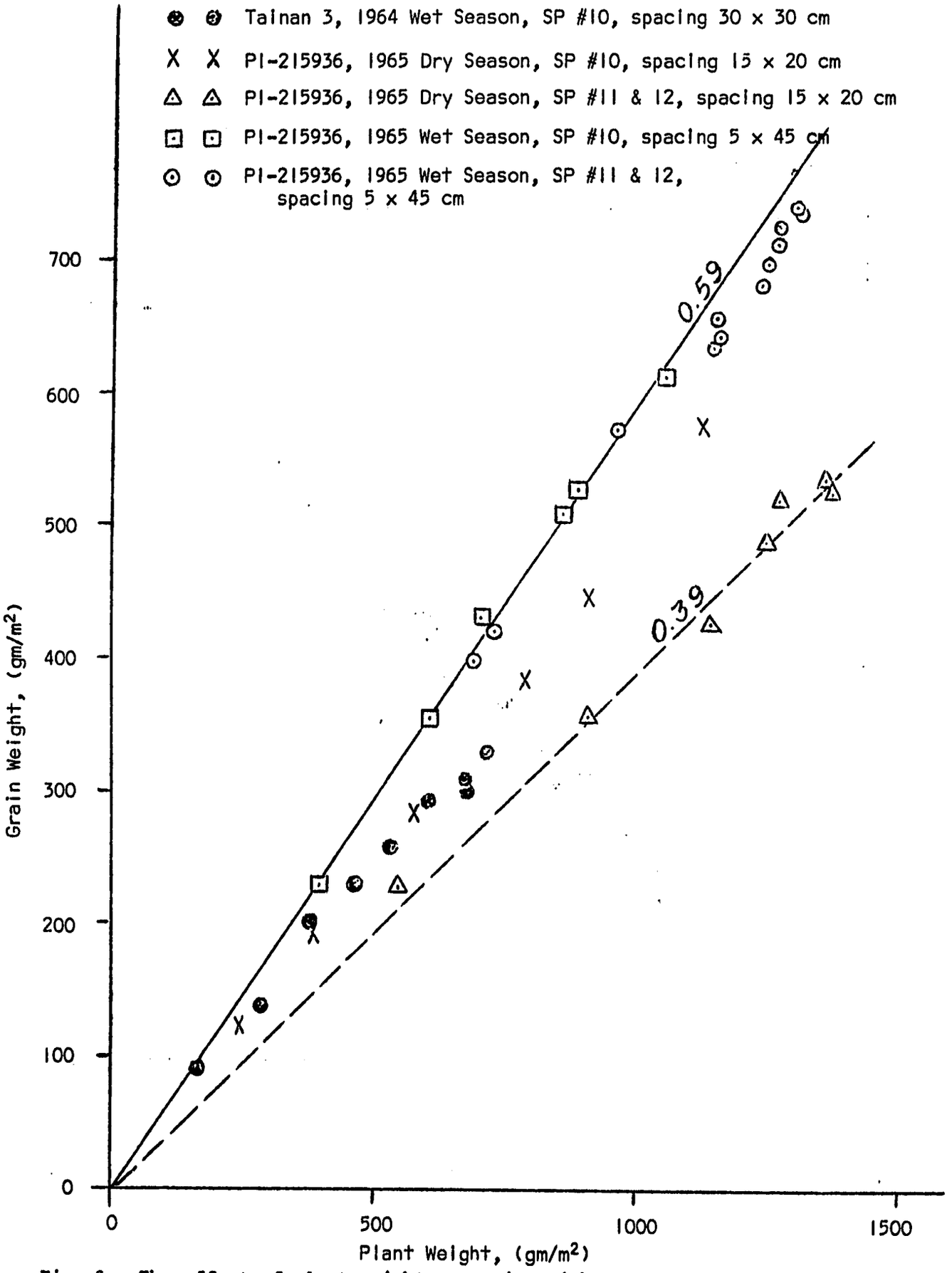

Fig. 6. The effect of plant weight on grain weight per square meter.