Increase of Silage Corn (*Zea mays* L.) Productivity by Dense Planting

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Planting density is one of the major factors effecting productivity of corn plants. The density effect on production varied with climatic conditions, fertilizing levels, varieties, sowing times, etc.[6,8,11,12,17] To determine what planting density can maximize the yield under a given environmental condition of each region is very important in corn cultivation. For instance, in the Corn Belt of the USA, a density of around 5,000 plants/10 a (are) has been recommended for grain production,[6] while a little higher densities, 7,000 to 8,000 plants/10 a for silage production.[2,7,15,16] Thus, in the Corn Belt corn plants are grown at relatively low densities.

Reasons why corn yield is reduced at higher densities are as follows[3,4,5,6,11,12,17]: (1) growth delay, (2) reduced amount of substance distributed to ears, (3) appearance of barren plants caused by pollination trouble and others, (4) water deficiency and wilting due to increased transpiration with high LAI, and (5) lodging.

Many evidences [2,3,18] proving that at least 10,000 plants/10 a is required for silage corn production have been reported in Europe where climatic condition is quite different from that of the Corn Belt in the USA. According to Bunting et al.[3,4] in Britain, a density of 10,000 plants/10 a seems to be adequate for corn plants grown for silage in drier areas, but higher densities up to a maximum of 15,000 plants/10 a are justified in areas where soil water content is less limiting.

Hokkaido, the northernmost island of Japan accounts for about 35% of the total corn area in Japan. Tanaka and Yamaguchi[17] suggested that a highest dry matter production could be obtained by raising the density up to over 10,000 plants/10 a. At present, however, a considerablely low planting density, about 6,000 plants/10 a, is recommended as a standard for corn cultivation in Hokkaido. Silage corn production differs from grain production in that both stover and grain are similarly regarded as important yield components.[13,14] In this paper, increase of productivity of silage corn by dense planting is discussed in relation to climatic features in Hokkaido based on the data obtained from the experiments[10–12,18] carried out for three years from 1977 to 1979, using two leading hybrid varieties grown around Sapporo of Hokkaido, Caldera 535 (early maturing) and Pioneer 3715 (late maturing).

Climatic condition

As a prerequisite for discussing relationship between productivity and planting density, regional difference in climatic condition has to be recognized.[9] The Corn Belt (40° to 45° N.L.) in North America, and Western Europe (around 50° N.L.) are characterized by continental and oceanic climatic condition, respectively. Hokkaido (42° to 45° N.L.) is located in the northern part of Asia temperate monsoon zone.

In order to clarify climatic features of these regions, an area representing the typical climatic feature of the region was chosen for each region: Sapporo (43°03′ N.L., 141°20′ E.L.) of Hokkaido, Moline (41°27′ N.L., 90°31′ W.L.) of the USA and Oxford (51°46′ N.L., 01°16′ W.L.) of Britain.

Monthly air temperature, solar radiation precipitation and day length at the three areas are given in Fig. 1. In Moline, where corn is grown in general at comparatively low densities, a favorable air temperature (around 22° to 26°C in daily mean air temperature)[9,10] for corn growth continues as long as three months in the summer. The solar radiation during the whole

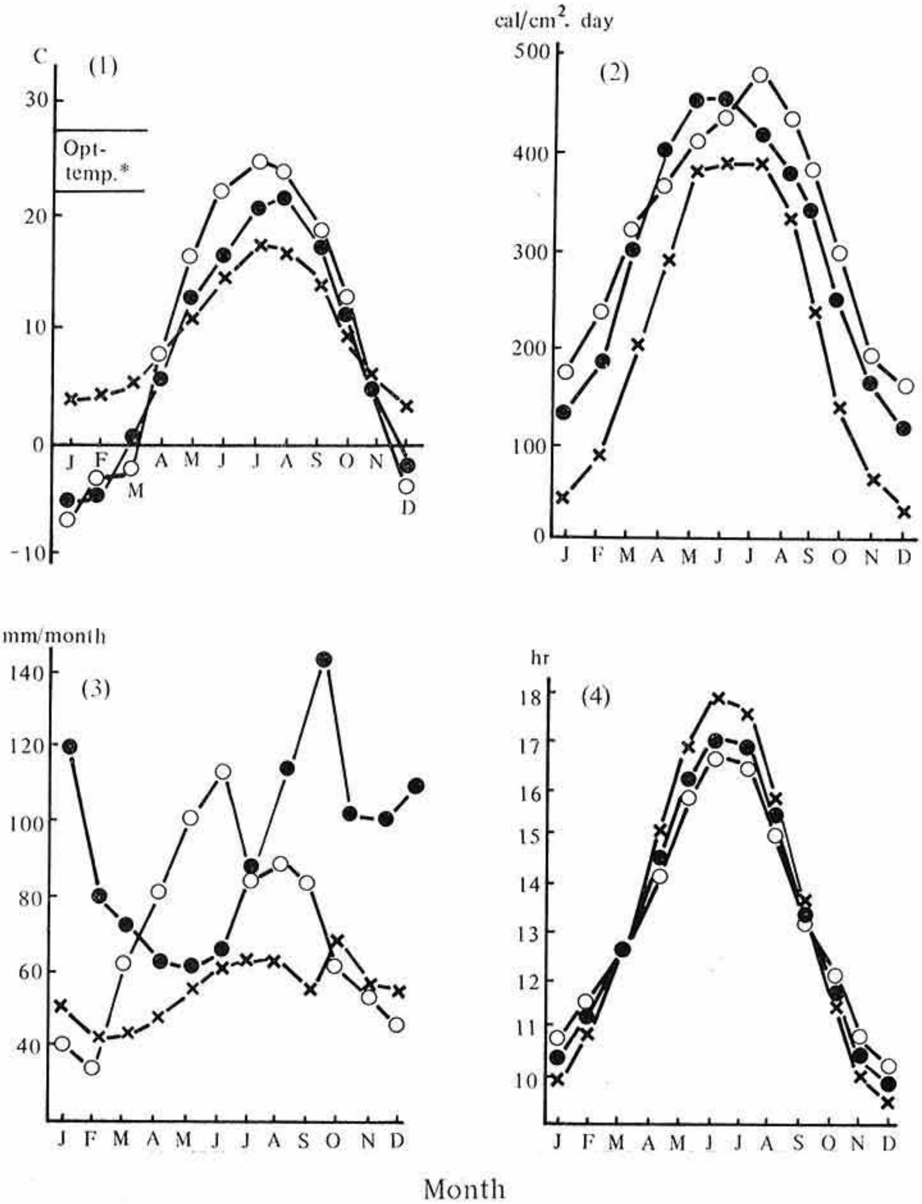

Fig. 1. Monthly variations in daily mean air temperature (1), solar radiation (2), precipitation (3) and day length (4) at Sapporo (43°03′N., 141°20′E), Moline (41°27′N., 90°31′W.) and Oxford (51°46′N., 01°16′W.).
*: Range of optimum air temperature (22～26°C) for corn growth.
● Sapporo; ○ Moline; × Oxford

growing season (about 180 days; the number of days with daily mean air temperature exceeding 10°C) is also comparatively high with its peak around July (middle growth stage). The precipitation increases in the spring (shoot emergence to early growth stage) and decreases in the autumn (maturing growth stage). From the view points of air temperature and solar radiation, the environment of Moline is likely favorable to corn production. However, at the late growth stage (July to October) water deficiency and wilting of plants may be caused by reduced precipitation. Especially at high densities LAI becomes so large that water deficiency and wilting might often be sever in the absence of irrigation.

Oxford, where corn is grown with extremely high densities, has a comparatively low air temperature, not reaching the lower limit of the favorable air temperature even in the midsummer. The growth period is relatively short (150 days). The range of seasonal differences in air temperature is narrow. Also, the precipitation is less and almost without monthly variation. The precipitation at the late growth stage is about 75% of that of Moline. However it may be assumed that plants do not suffer from water deficiency so severely even at high planting densities since both the solar radiation and air temperature are considerably lower. The day length during the growth season from spring to autumn is longer than that of Moline.

In Sapporo, the seasonal variation of air temperature is almost similar to that of Moline, but the air temperature during the corn growth season is, as a whole, rather low, not reaching the range of favorable air temperature until the midsummer. The growth season (about 160 days) is shorter than in Moline and a little longer than in Oxford. The seasonal variations of solar radiation and precipitation show inverse patterns to those of Moline, that is, the solar radiation is higher in the spring and lower in the summer to autumn, while the precipitation is less in the spring and becomes much in the autumn. The day length during the growth season is shorter than that of Oxford and almost similar to that of Moline.

Solar radiation and dry matter production

Influences of shading treatments at different growth stages on the final yield of corn are shown in Table 1. Without exceptions, the yield was reduced as the treatment became intensive. The shading effect, however, differed with treatment stages; the middle stage treatment (July 22 to Aug. 28) was most influential but the early stage treatment (June 29 to July 22) was almost ineffective. The shading throughout the whole growth period (July 29 to Oct. 12) was relatively less influential as compared with the middle and late stage treatments, suggesting that plants may have adapted themselves to the lower solar radiation with a result of a relatively high productivity. This fact implies that, even in regions having a low solar radiation like in Oxford (Fig. 1), the productivity might not

Table 1. Influences of shading treatments during different growth stages on final yields of the two hybrids

Periods of shading treatments	Whole growth stage, Jun. 29～Oct. 12 (106 days)			Early stage, Jun. 28～Jul. 22 (24 days)		Middle stage, Jul. 22～Aug. 28 (38 days)		Late stage, Aug. 20～Oct. 12 (53 days)	
Light intensity	100%	75%	60%	75%	60%	75%	60%	75%	60%
Supplied solar radiation (cal/cm². Whole growth season)	40,403 (100)	30,302 (75)	24,242 (60)	37,768 (93)	36,186 (90)	36,689 (91)	34,456 (85)	35,829 (89)	33,083 (82)
Caldera-535									
Whole Crop Wt. (D.M. kg/10a)	1,551.0 (100)	1,464.1 (94)	994.1 (64)	1,585.1 (102)	1,484.2 (96)	1,378.4 (89)	1,076.2 (69)	1,470.0 (95)	1,156.4 (75)
Ear Wt. (D.M. kg/10a)	999.1 (100)	935.1 (94)	594.9 (60)	1,049.0 (105)	1,050.0 (105)	900.1 (90)	568.0 (57)	992.6 (99)	831.6 (83)
Pioneer-3715									
Whole Crop Wt. (D.M. kg/10a)	1,938.0 (100)	1,591.9 (82)	1,185.8 (61)	2,105.8 (109)	1,915.1 (99)	1,828.6 (94)	1,557.8 (80)	1,784.4 (92)	1,431.5 (74)
Ear Wt. (D.M. kg/10a)	1,248.0 (100)	944.9 (76)	619.3 (50)	1,349.8 (108)	1,239.0 (99)	1,089.3 (87)	753.1 (60)	1,122.1 (90)	892.7 (72)

Note: Figures in parenthesis indicate percentages to the control. Planting dengity=5300 plants/10a.

necessarily decrease so much. Also, the productivity-response to light conditions seems different among varieties; some of which are more adaptable or tolerable to the shortage of solar radiation.[9,18]

When the shading treatment (60% of the full sunlight) was imposed at the middle stage the whole crop and ear weight markedly decreased to 69% and 57% in Caldera 535, and also to 80% and 60% in Pioneer 3715, respectively, though the decrease of solar radiation was only 15% of the total solar radiation during the whole growth period (Table 1). This accounts for that the climatic condition of Sapporo (Fig. 1), where solar radiation tends to reduce from the middle to the late growth stage, may not be favorable to grain production. Especially at high planting density an intensive mutual shading in the population causes the grain yield reduction. Contrary to this, regions, like Moline, having a high solar radiation at middle to late growth stage may be regarded as adequate for grain production.

Changes in dry matter production with planting density

1) Dry matter weight

Effects of planting density on dry weight of whole crop (stover+ear) and ear, ear-ratio (ear weight/whole crop weight), and TDN (Total Digestable Nutrient) yield are presented in Fig. 2. At the time of harvest (Oct. 4) the dry weight

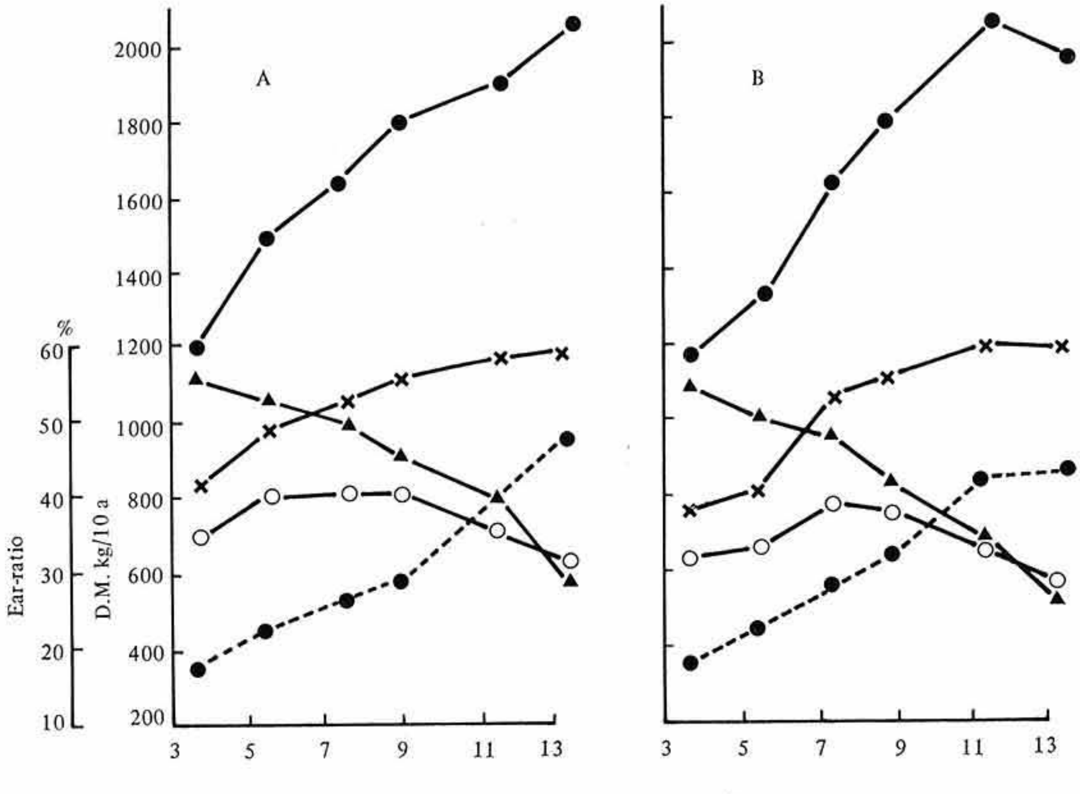

Fig. 2. Effect of planting density and fertilizer level (A and B) on whole crop weight (—●—), TDN (—×—, Total Digestable Nutrient Yield), ear weight (—○—) and ear-ratio (—▲—, % of ear weight to whole crop weight) at the harvesting (Oct. 4), and whole crop weight (···●···) at the flag leaf stage (Aug. 23) of Pioneer 3715.

Notes: Whole crop weight=stover weight + ear weight. Fertilizer level A and B: See the note of Table 2.

of whole crop and TDN yield were greater with increasing density, attaining about 2,000 kg/10 a in dry matter of the whole crop at higher densities over 10,000 plants/10 a. This value exceeds, by about 30%, the dry weight (1,500 kg/10 a) observed at the standard planting density (6,000 plants/10 a) recommended in Hokkaido. Also at the flag leaf stage (Aug. 9), increased weight of whole crop was observed with increased planting density.

The fact that the relation between whole crop dry weight and planting density at the harvesting time (Oct. 4) is in parallel with that of the flag leaf stage indicates that the latter was kep unchanged until the final harvesting time. It suggests that the increase of the dry matter accumulated during the vegetative growth stage may directly cause the increase of final yield.

There were no large inter-density differences in dry weight of ear, though only a little higher values were shown at 7,000 to 9,000 plants/10 a. The ear-ratio decreased markedly with increase in density.

Dense planting or low solar radiation may often cause lodging and barrenness, although no lodging occurred with Pioneer 3715 and Caldera 535, at higher densities over 10,000 plants/10 a in three years of experiment. As it is known that some hybrids show a genetic feature of high tolerance to high density or low solar radiation[9,15,17,18], varieties more tolerable to both dense planting and low solar radiation are required to be developed to obtain a stable, high yield in Sapporo or the central area in Hokkaido.

2) Crop growth rate

Changes in CGRs of whole crop and ear with planting density are shown in Table 2 for the whole growth stage (May 20 to Oct. 4), vegetative growth stage (shoot emergence stage, May 20 to flag leaf stage, Aug. 23) and maturing growth stage (flag leaf stage to maturity, Oct. 4). In addition, the accumulated effective air temperature and accumulated solar radiation at each growth stage are also shown. CGRs of the whole or vegetative growth stage increased, as the planting density rised, while, at the maturing growth stage, planting densities over 7,254 plants/10 a showed almost no effect on CGR.

In spite of that the accumulated effective air temperature and accumulated solar radiation at the vegetative growth stage were much larger than those of the maturing growth stage, the mean CGR, 6.90–7.45 $g/m^2 \cdot day$ obtained at the vegetative growth stage was much less than that of the maturing growth stage, 18.19–19.55 $g/m^2 \cdot day$. This result suggests that the increase of crop photosynthesis or drymatter accumulation during the vegetative growth stage may effectively increase the CGR of whole growth stage and final yield.

For the ear a little higher CGRs were found at densities of 7,254 or 8,966 plants/10 a (Table 2). The ratios of the CGR of ear to that of whole crop at the maturing growth stage were 75 to 80% at densities below 8,866 plants/10 a, but at the highest density (13,300 plants/10 a) the ratio decreased to 50%. This means an reduced translocation to the ear at higher densities.

Joint-effect of planting density × fertilizing level on dry matter production was not so clearly shown (Fig. 1 and Table 2), although apparent effects were recognized by Tanaka and Yamaguchi,[17] and Iwata[8].

3) Leaf area index

Changes in mean LAI ($\overline{LAI}$) at different growth stages with planting density are shown in Fig. 3A, and the light extinction coefficient (k) in plant population in Fig. 3B. $\overline{LAI}$ increased with increasing planting density at any growth stage, and k was 0.45. At the early growth stage when LAI is still small, an increase of LAI can directly raise the solar energy utilization efficiency and hence crop photosynthesis. At this stage, an increased LAI may not cause water deficiency and wilting due to an increased transpiration, because LAI is not so large even at the highest density (13,300 plants/10 a). In Sapporo the rainfall shortage at the early growth stage, as shown in Fig. 1, may be a main cause of water deficiency.

At the maturing growth stage CGR showed no apparent increase with the increased planting density (Table 2), though $\overline{LAI}$ increased largely from 3 up to 9 (Fig. 3A). The reasons for this may be as follows: (1) The light interception ratio by leaves has, as shown in Fig. 3B, already exceeded 75% even at the lowest density (3,627 plants/10 a, $\overline{LAI}$=3.0) and (2) the solar radiation

Table 2. Effect of planting density, fertilizer level (A and B) and climatic condition on CGR of whole crop and ear

Plant part and growth stage		Fertilizer level*	Crop growth rate (g/m^2 day) at planting density (no. plants/10a) indicated below: 3,627	5,320	7,254	8,866	11,400	13,300	Mean	Growth period	Ac. ** Effec. Temp. (°C)	Ac.*** Solar Rad. (cal/cm^2)
(A)	Whole crop	A	8.82	10.33	11.23	12.18	12.93	14.60	11.52	138 days	923	55,938
	(whole growth period)	B	7.81	9.10	11.53	12.19	13.34	13.01	11.16	(May 20-Oct. 4)		
(B)	Whole crop	A	3.46	4.07	5.20	7.44	10.15	11.07	6.90	82 days	513	36,488
	(vegetative stage)	B	4.05	5.82	6.68	7.60	9.94	10.61	7.45	(May 20-Aug. 9)		
(C)	Whole crop	A	17.91	18.73	19.05	20.86	18.86	21.86	19.55	56 days	410	19,450
	(maturing stage)	B	14.41	15.20	20.27	20.66	20.21	18.39	18.19	(Aug. 9-Oct. 4)		
(D)	Ear (maturing stage);	A	13.44 (75)	14.56 (78)	15.20 (80)	15.04 (71)	13.60 (71)	11.24 (50)	13.85	56 days		
	$\frac{(D)}{(C)}$	B	11.49 (80)	12.13 (80)	14.78 (72)	13.45 (64)	12.01 (58)	9.09 (49)	12.16	(Aug. 9-Oct. 4)		

Notes: * Fertilizer level A: Nitrogen applied at the rate of 3.4 g/plant, so that actual application, N kg/10a, for each planting density was 12.4, 18.2, 24.8, 30.3, 38.9, and 45.4

B: Nitrogen applied at the rate of 18.0 kg/10a, irrespective of planting density.

** Accumulated effective-temperature (=day × (mean daily air temperature − 10°C)).

*** Accumulated solar-radiation.

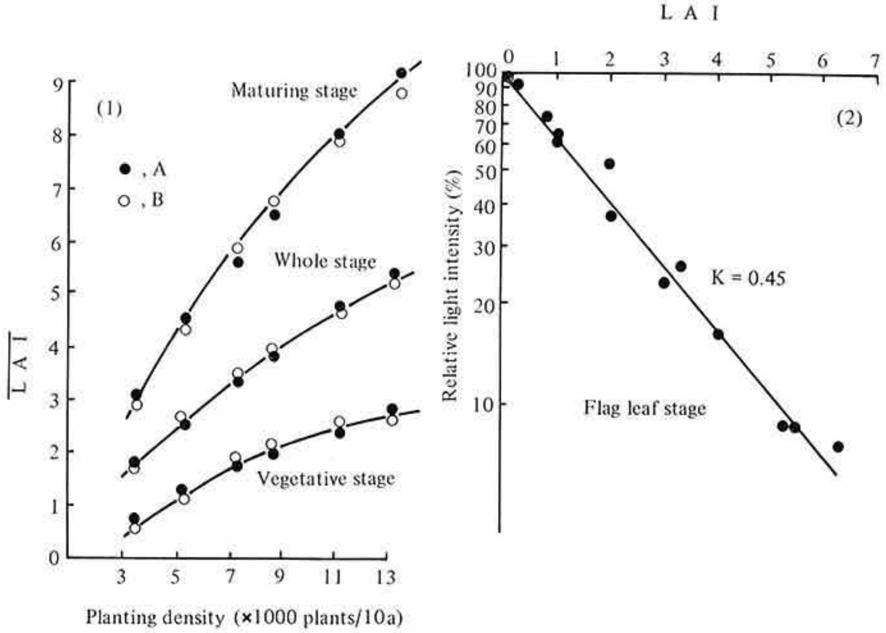

Fig. 3. Relationship between planting density and $\overline{LAI}$ (mean Leaf Area Index) during different growth stages (1), and between LAI and relative light intensity in the population (2).

Notes: k is a light extinction coefficient;

Vegetative stage, May 20 ~ Aug. 9; Maturing stage, Aug. 9 ~ Oct. 4;
Whole stage, May 20 ~ Oct. 4.
Variety used: Pioneer 3715
A.B.: Fertilizer level

tends to decrease at this stage (Fig. 1), so that it can not be expected that the light utilization and crop photosynthesis are increased very much by raising density, and (3) at high densities the respiratory loss in plant population increases.

However, since the precipitation in Sapporo increases from summer to autumn (Fig. 1), water deficiency and plant wilting can not occur so frequently or seriously even at high planting densities.

Relationships between LAI and NAR (Net Assimilation Rate) or CGR during the whole growth season are shown in Fig. 4. The relationship between NAR (y) and LAI (x) was expressed by the regression equation, $y=6.526\exp(-0.1728x)$. The equation for CGR, $Y=6.526x\exp(-0.1728x)$ is derived by multiplying the above equation by LAI (x); because CGR $(Y)=NAR\times LAI$. Differentiating this equation with respect to x leads the equation, $Y=1.1275(5.787-x)\exp(-0.1728x)$. This equation indicates that, CGR takes a maximum value, 13.88 $g/m^2\cdot day$, when LAI is 5.787. These values may predict that the dry matter production could be maximized at a planting density (probably about 15,000 plants/10 a) higher than the highest density (13,300 plants/10 a, $\overline{LAI}=5.2$; refer to Fig. 3A) adopted in this study.

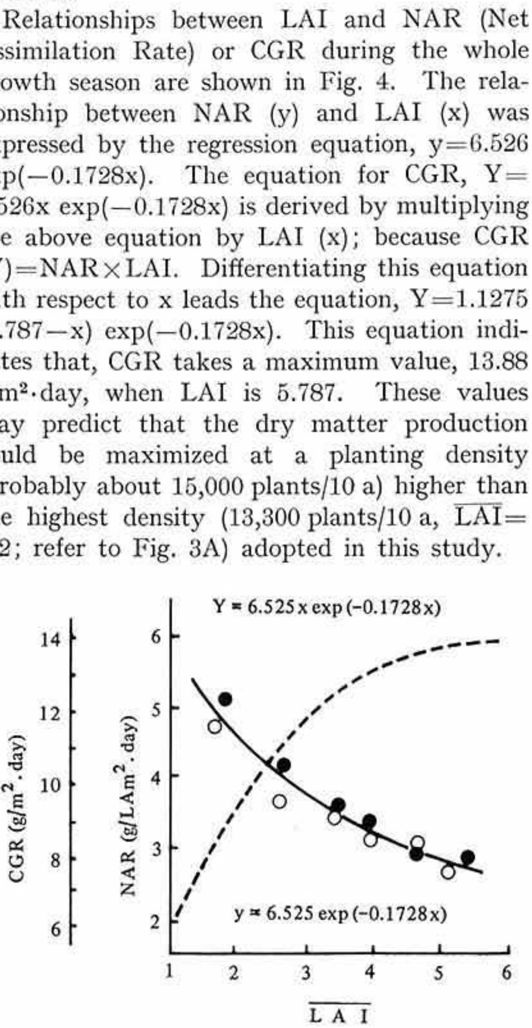

Fig. 4. Relationship between Net Assimilation Rate (NAR,—) or Crop Growth Rate(CGR, ---) and $\overline{LAI}$ (mean Leaf Area Index) during the whole growth season (May 20~Oct. 4)

Note : Pioneer 3715
● : Fertilizer level A, ○ : B

Conclusion

(1) It may be suggested that a higher density over 10,000 plants/10 a is required to obtain a high yield of silage corn in Sapporo or the central area of Hokkaido.

(2) Increase of dry matter accumulation during the vegetative growth stage can lead the increment of final yield (stover+ear).

(3) Dry matter production during the vegetative growth stage is markedly increased with increase of planting density.

(4) To obtain a stable, high yield, varieties more tolerable and adaptable to dense planting and shading are required to be developed.

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