ENGINEERING AND ECONOMIC ANALYSIS OF CARBON DIOXIDE FERTILIZATION FOR TAIWAN'S AGRICULTURE

Thesis for the Degree of M. S.
MICHIGAN STATE UNIVERSITY
Tung Liang
1963

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of the requirements for

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H. F. McColly
Major professor

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AN ABSTRACT

Submitted to the Colleges of Agriculture and Engineering of
Michigan State University of Agriculture and
Applied Science in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
AGRICULTURAL ENGINEERING

Department of Agricultural Engineering

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Approval H. F. McColly

AN ABSTRACT

Carbon dioxide fertilization has been proven biologically sound by many experiments in greenhouses and field plots, but it has never been adopted as a regular practice by farmers. Lack of knowledge between pure experimental results and actual methods of conducting the operation is suspected to be the cause of this long postponement.

This study is intended to investigate this knowledge gap and try to bring it one step forward to the fulfillment of this promising experimental result, which may help solve most of the food shortage problems faced by the world.

The method of approach to this study is outlined below.

1. According to the nature of operation, carbon dioxide fertilization was broken down into two categories, namely:

   a. Absorption or biological phase

   b. Distribution or engineering phase

   The former covers the carbon dioxide movement from the release of the distribution point to the conversion into a part of the plant body and the latter phase covers the carbon dioxide movement from central source to the point of release.

2. Simple equations for the relationship of parameters involved were derived. With the equation, the two phases mentioned could be evaluated precisely and

corresponding measures could be decided to improve the whole operation.

3. Basic parameters for a few crops were collected and a trial distribution system was also designed following the design procedure organized in this study.

Based on this trial design and the limited data, a rough conclusion was reached that carbon dioxide fertilization is a highly profitable practice. A few criteria values were also obtained for the two different phases as a guide to maintaining the operation in the profitable range.

It is the intention of this study to formulate a way to explore this subject and also determine if further study is necessary instead of trying to reach any definite conclusion and the work done so far encourages further study. Therefore, the conclusions tendered in the last chapter will need modification either when more precise knowledge of parameters are available or better distribution system is invented. Nevertheless, this study has fulfilled its objective.

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INTRODUCTION

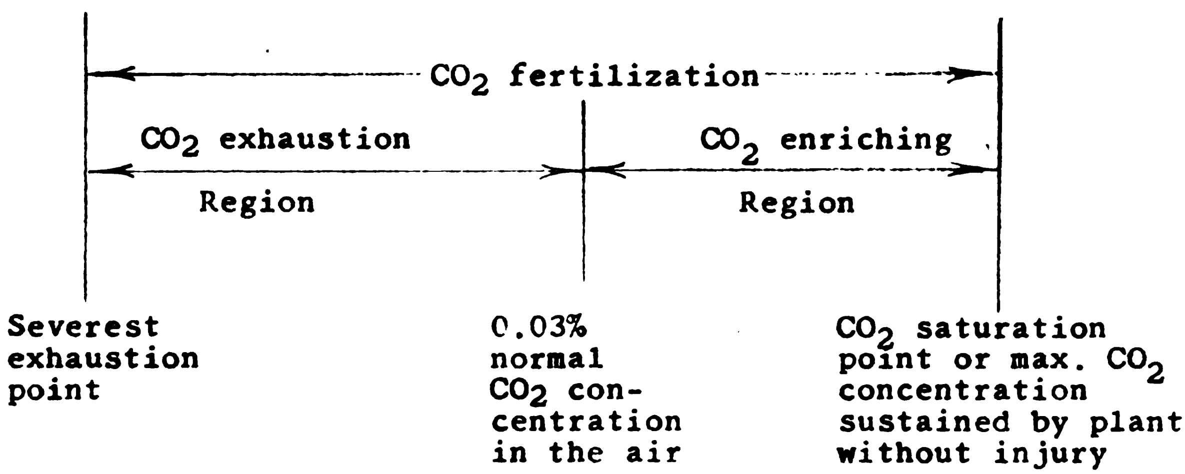
Food shortage has always been a challenge to the agricultural scientists in the densely populated countries and eventually more countries will feel the pressure of this problem in the very near future if the growth of world population continues at the present rate of 50 million per year. Unfortunately, Taiwan ranks almost highest in the population density list. For the past twelve years, breeding of new species, increasing fertilization, and many other measures have been adopted to increase the land yield to meet the 3.5 per cent annual population growth rate and keep the living standard fairly high among the southeast Asian countries. However, recently the positive tendency started to level out and no major increase seems to be possible; therefore, lowering of living standard seems to be the only temporary solution to feed the growing population if no other new measure could be introduced in time.

Since all easy-to-adapt scientific knowledge has already been exhausted in the increasing of unit land yield and all arable land has already been converted into farms, it is natural for people to try to reclaim marginal land, such as tidal basin and mountain land. Experiments on these methods started a few years ago, although it is technically possible to grow crops in these lands, but the high cost of reclamation (2,500 U. S. \$/ha to 6,000 U. S. \$/ha) makes the cost of food production even higher than purchasing them abroad.

On the other hand, carbon dioxide fertilizer on a greenhouse basis has provided definite yield increase, but it has never been extended to ordinary farming in spite of its great potentiality of food increasing power which has already been proved by many experiments conducted in many European countries as well as by a few scientists here. In view of its promising past result and the world food demand, the need for further investigation is obvious.

However, past experiments were entirely restricted to the objective of proving biologically the possibility of increasing crop yield by enriching air with CO_2 and no consideration was given to the technique and economic phases of this problem. But the success of carbon dioxide fertilization will depend very much on the invention of a technique which may administer CO_2 economically as a fertilizer (if it is economical by nature). Furthermore, the term "CO_2 fertilization" in the past only stood for the practice of enriching air with CO_2 to eliminate partially or completely the CO_2 as a limiting factor in the photosynthesis process, but many experiments concerning microclimate and in the field of plant physiology (cited in Literature Review) definitely discovered that CO_2 exhaustion phenomenon exists in the immediate vicinity atmosphere of crops actively under photosynthesis and crop wind braking power aggravates further this problem (especially air within crops). It would be intuitively felt that not only by enriching air with CO_2 but a method of increasing air circulation would also increase crop yield. Therefore, "CO_2 fertilization" used hereafter in this study will be broader in meaning and defined as follows:

"Carbon dioxide fertilization is a practice by which the yield of crops can be increased through elimination partially or completely of CO_2 as a limiting factor." A simple diagram below may help clear the idea.



As mentioned above, CO_2 fertilization is an economic practice and it also has been biologically proven sound. The immediate step would be an economic analysis from the point of view of application technique. This evaluation will tend to be rather approximate in nature; nevertheless, it would yield knowledge to estimate if any further experiments are necessary and also the very kind of experiment needed if it could be administered economically at the present level of technology. In short, this study will try, basing on available engineering knowledge and agricultural science, to evaluate the economical possibility of using this method to increase food for the densely populated countries.

This investigation will concentrate on the following three major phases of the problem and be conducted accordingly.

1. Derivation of an absorption economy equation for the determination of net economic return for every unit carbon investment.

2. Study of controllable factors affecting absorption economy.

3. Engineering evaluation of the method of eliminating CO_2 as a limiting factor.

In view of the nature of past experiments in this subject, this one will be an entirely new and also indispensable study for the realization of "CO_2 fertilization" practice. It intends to continue the study from the place left by the agricultural scientists who have done their work splendidly by proving the possibility of increasing yield by CO_2 fertilization. It is the duty of an agricultural engineer to prove that it is also economically and engineeringly possible. But this study, even successful, will not immediately bring CO_2 fertilization into farms because many unknowns still exist, such as the optimum application time in the plant's life, corresponding fertilization change, et al. which will further require close cooperation between many different branches of science. But this investigation will serve its own purpose.

LITERATURE REVIEW

The conception of multiconditioned process was first recognized by Liebig and was expressed in his law of the minimum in regard to yield of field crops, which says, "The yield of any crop always depends on that nutritive constituent which is present in minimum amount." Apparently at that time Liebig did not consider light, water, CO_2, and many other factors which also influence the yield of crops as well as nutrients. Giving due credit to interaction of separate factors, Blackman, in 1905, stated his law of limiting factors in a broader term: "When a process is conditioned as to its rapidity by a number of separate factors, the rate of the process is limited by the pace of the slowest factor" and the classical example used by Blackman was the interaction of carbon dioxide and light. This law governs any physiological process. The special factors that influence the rate of photosynthesis may be grouped under the heading internal and external factors. In this study, the main interest will be concentrated in the external factor--carbon dioxide, which is treated as the limiting factor. The idea of this study is to improve this factor to the point where CO_2 will not be limiting the yield. The literature reviewed will be also confined within this subject and presented in the following sequence.

1. Information about CO_2 as the limiting factor.

   a. Environment
   b. Photosynthesis curves

2. Enrichment experiment results to prove the idea is practical.

3. Types or methods of enriching and their respective merits.

4. Other related literature.

   a. CO_2 exhaustion
   b. Crop wind braking power
   c. Penetration of radiation within plant cover
   d. The absorption of CO_2 by the leaf and its efficiency
   e. Air pollution problem

Carbon Dioxide as the Limiting Factor

Although either light or supply of carbon dioxide could be the limiting factor of photosynthesis process of a plant, many experiments show that even under moderate light intensity, the carbon dioxide concentration rather than light acts as the limiting factor. There are many carbon dioxide curves of different plants and the one reproduced in Figure 1 is the wheat carbon dioxide curve by Hoover, Johnston, and Brackett in 1933.

It is obvious from the curve that, even at such a low light intensity as 630 F.C., the saturation point of carbon dioxide concentration is still much higher than 0.1 per cent (by volume) which is almost three times the normal CO_2 content in the air. From the many carbon dioxide curves available and the strong light intensity on the earth (light intensity in summer about 10,000 to 12,000 F.C. was reported

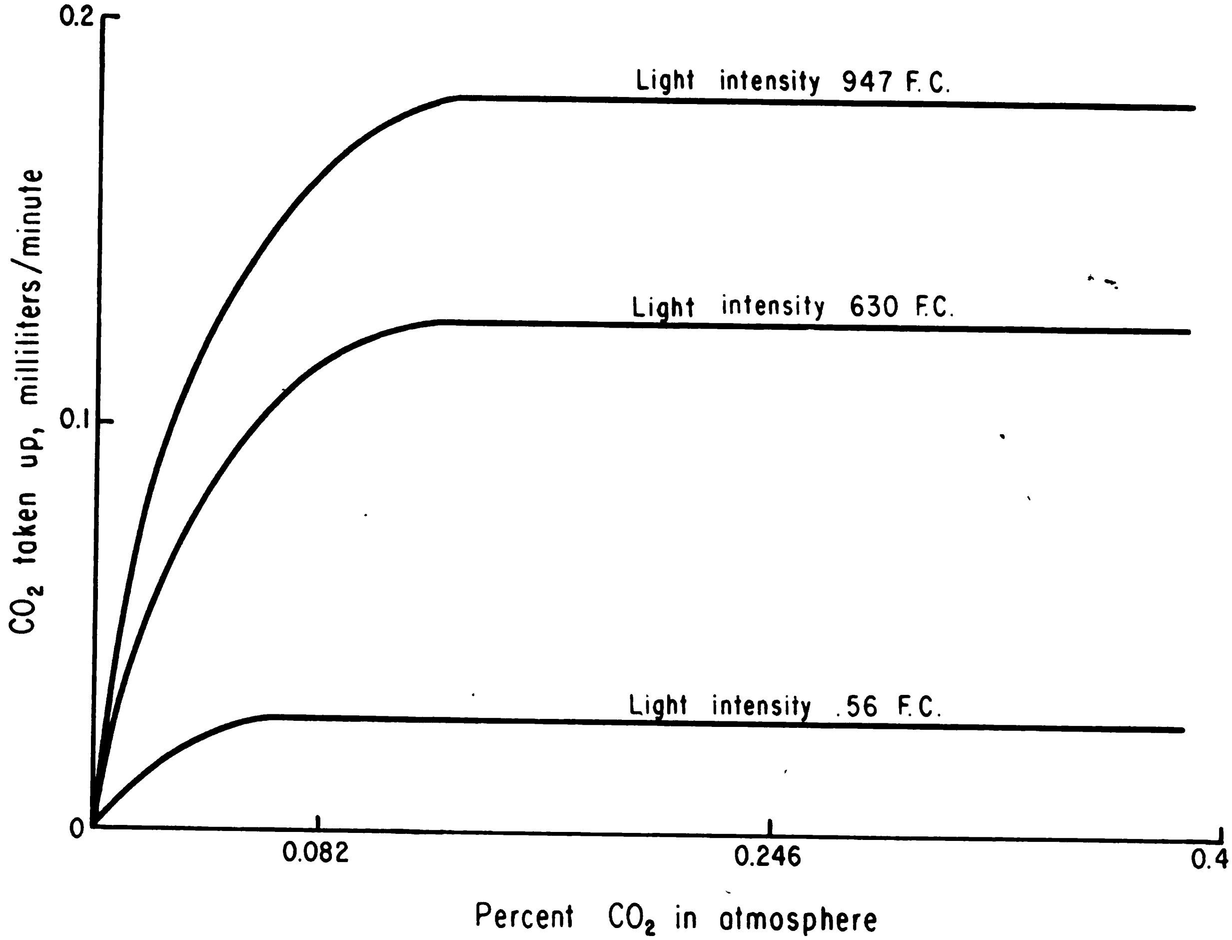


Figure 1 Carbon Dioxide Curves for Wheat

by Withrow in 1936), it is reasonable to expect that enriching the air with carbon dioxide will lead to a proportionate increase in crop yield. Experimental results tend to confirm this conclusion.

Enrichment Experiment

The knowledge gained from carbon dioxide curves naturally leads the scientist to experiment with the possibility of using CO_2 as a fertilizer to increase crop yields. Many experiments of this nature were conducted both in the United States and many European countries, especially in France and Germany.

Although Brown and Escombe (1902) and Demoussy did the first work at the same time in applying increased amounts of carbon dioxide to plants on a relatively large scale, it was Demoussy who first achieved success and obtained an increase in dry weight of 158 per cent for those plants growing under conditions of carbon dioxide fertilization.

In practically all cases where the carbon dioxide supply to field and greenhouse crops has been increased, beneficial results have been obtained as measured by increased yield of grain, fruit, or amount of dry matter produced. In Europe, H. Fischer (1912 to 1927) has purified the carbon dioxide from the gases that emanate from smelter furnaces and conveyed it in pipes to greenhouses and field plots. By these means, increased yields and more vigorous growth were obtained with potatoes, beets, tomatoes, and bush beans.

Favorable results from CO_2 fertilization have also been obtained by Riedel (1919, 1921), Cummings and Johns (1918, 1920), Jess (1920), Borneman (1920), Owen, Small and Williams (1926), and Gradenwitz (1920). The results of Riedel's studies are listed below:

Crop (planted in a glass house)	Increased Yield (check 100%)
Tomato	275%
Cucumber	335%
Spinach	250%
Potato	290%
Barley	200%

Riedel also reported that crops grown in field plots gave yields varying from 1-1/2 to three times over those of unfertilized check field plots.

Jess (1921), in field experiments with Irish potatoes, increased the average weight of the tubers from 140 to 330 grams by the application of CO_2. In greenhouses, the yield of tomatoes was increased from 29.5 kilograms for an untreated house to 81.3 kilograms for the treated one, while the yield of cucumbers was increased from 138 to 235 kilograms.

In this country, the most extensive work on carbon dioxide fertilization has been done by Cummings and Jones (1918, 1920) in greenhouses and the plants were grown in large open containers by the size 26 inches high, 26 inches long, and 18 inches wide. Their results are listed as follows:

Crop	Net Increase (check 100%)
Beans (seed only)	132% - 304%
Beans (dry pod only)	172% - 243%
Peas (total dry matter)	118% - 217%
Potatoes (no. of tubers)	146%
Peas (dry seed)	267% - 391%
Potato (gain in weight of each tuber)	107% - 425%
Strawberry	180%

These experiment results tend to confirm that the hypothesis of considering CO_2 as a limiting factor in the photosynthesis process and also enriching air with CO_2 to increase crop yields are biologically possible.

Methods of Enriching

Past experiments of CO_2 fertilization were conducted mainly in three different ways: (1) plants grown in small glass containers or compartments, (2) in greenhouses, and (3) in field plots. The results cited in the last paragraph are either of greenhouses or field plots. Negative results were reported by Brown and Escombe (1902), also by Cummings and Jones (1918, 1920), and others. But the negative results were obtained only from experiments in which plants were grown in small, closed compartments and CO_2 concentration variation was large. It is also believed, in addition to this CO_2 nonhomogeneity, such as high humidity, temperature, etc., many other external factors induced by the practice of enclosing plants in small compartments also have harmful effects on plants. However, experiments conducted in greenhouses and in fields produced only positive results.

In short, past work in this topic has been attempting to prove the biological possibility of increasing yield by improving the limiting factor. The CO_2 supply of the photosynthesis process and experimental results in this respect also unanimously confirmed this theory. Although the experimental results were so promising and most of the world hungry for more food, this result has never been put into actual practice. The author believe that it may be due to lack of information about the economic and engineering (method of application) phases which greatly hinder the utilization of this proven fact. Therefore, a further investigation of this problem from the engineering point of view should be valuable.

Other Related Experiments

Besides those cited above, there are many other important facts relating to CO_2 fertilization worthy of being cited here.

CO_2 Exhaustion

In addition to the ingeneous successful experiments of enriching the air with CO_2 to increase photosynthesis rate, another phenomenon of CO_2 exhaustion existing in the immediate vicinity of plants found by culture both in solution and in field experiments may also suggest that the photosynthesis rate can also be increased tremendously without even increasing the CO_2 concentration in the air. A method of ventilating or stirring air may wipe out this exhaustion effect and leaves would be exposed to air with normal CO_2 concentration.

Lundegardh (1921), Kreusler (1885, 1887), and Singh and Kuman (1935) discovered this exhaustion phenomenon and later demonstrated by Kostycher et al. (1927) and Chesnokov and Bazyrina (1932). They also discovered that, not only the rate of circulation of air and solution, but also the size and shape of the plants may be of importance too. Another interesting experiment in corn fields showed that CO_2 concentration of the air may drop to 0.001 per cent on windless days from the normal 0.03 per cent, and this is only the average value of the air in the corn field. It is very reasonable to suspect that air in the immediate vicinity of leaves will be tremendously low. Consequently, a very low rate of photosynthesis may only be too natural.

Crop Wind Braking Power

In 1915, G. Hellman, in discussing wind reasearch at Nauen, stated that an anemometer placed at a height of two meters lost velocity if the grass beneath it was grown.

A. Koelsch stated about the calm prevailing within the plant cover during a storm, "It seems as though one had dropped into a sink-hole: above the elements battle, but under the plant cover hardly a breath is felt."

How much this braking power has further aggravated the CO_2 exhaustion is unknown now, but it is almost positive that this must further make the CO_2 exhaustion effect worse.

The Penetration of Radiation Within Plant Cover

If light intensity is seriously reduced by plant cover, then the CO_2 exhaustion within the plant cover will not have serious effect on the photothesis because light instead of CO_2 would act as the limiting factor. But measurement by A. Angström in one meter high grass and bare ground shows that CO_2 still will be the limiting factor. At 50 centimeters above the ground (50 centimeters below the plant cover), the intensity weakens only from 1.08 calories per square centimeter per minute to 1.04. In view of the fact that light intensity is, in most cases, abundant, this small change will not affect the fact that CO_2 still acts as the limiting factor.

How CO_2 is Absorbed by the Leaf and Its Absorption Power

Brown and Escombe (1900) showed that a leaf takes CO_2 from quiet air almost as rapidly as an equally large surface of alkali solution. It was soon found that this high rate of diffusion has nothing to do with the physiological properties of the leaf, but is a general property of multiperforate septa, i.e., barrier containing many small openings. Therefore, the absorption of CO_2 through stomata by a leaf is purely a diffusion problem within reasonable range, e.g., the higher the gradient of CO_2 the higher the absorption, providing the CO_2 is still the limiting factor of photosynthesis rate. And this is usually true under average to high light intensity.

The efficiency of leaf surface and its stomata can be illustrated by an experiment with corn in which 100 liters of air was drawn through a cellophane envelope containing about 100 cm^2 of the tips of corn leaves. The air made irregular contact with the leaf in a stream as much as one centimeter thick and passed over the leaf in an average time of less than two seconds. At this speed, with the stomata so nearly closed that no opening could be observed microscopically, 50 to 75 per cent of the CO_2 was removed from the air stream by the absorbing leaf. It may be concluded that the leaf is highly efficient in CO_2 absorption as long as enough CO_2 is available in the immediate air surrounding the plant.

Air Pollution by CO_2 due to Enriching Air with CO_2

Carbon dioxide is colorless and odorless, only harmful when it reaches the concentration of 0.5 per cent by volume, which is almost seventeen times the average CO_2 content in normal air. Enrichment practice seldom requires CO_2 concentration over 0.2 per cent (six times enrichment) and further increase of CO_2 enrichment is not economical due to high diffusion loss and light saturation phenomenon. Therefore, CO_2 enrichment will not pollute the air as far as human health and comfort are concerned.

ABSORPTION ECONOMY

Absorption economy will only reveal the economic relationship of carbon invested (or applied) and net extra economic return in crop yield without consideration of carbon dioxide distribution power cost, equipment depreciation, labor cost, and other necessary expenditures which may be involved in the carbon dioxide fertilization practice. Absorption economy depends on two factors:

1. Net salable crop return for each unit weight carbon absorbed by plants.
2. The quantity of carbon dioxide applied for each unit weight carbon absorbed.

Information about chemical composition of crop yield (including all plant parts), weight ratio between the different parts of the plant, and the respective prices for each part are necessary to calculate factor (1). The second factor may be determined if knowledge of carbon dioxide losses is known under proposed distribution methods. This matter will be investigated in the following sequence:

1. Derivation of a relation (Absorption Economy Equation) between the different factors.
2. Conduct a chemical analysis and a survey of weight ratios and prices of the different parts of a crop yield to obtain the various constants needed in absorption economy equation.
3. Collection of information about carbon sources and prices.
4. Use of absorption economy equation for rice.

5. Values for the various parameters in the equation.

6. Develop a nomogram for the solution of absorption economy equation.

7. The absorption economy for the four main crops in Taiwan.

Derivation of a General Absorption Economy Equation

Weight Ratio of Carbon to Total Matter: R

Salable products like grain, straw, etc. will be in natural marketing condition and non-salable products will be in dry matter condition.

$$R = \frac{W_s r_s + W_n r_n}{1} = \frac{\sum_i W_{si} r_{si} + \sum_i W_{ni} r_{ni}}{1}$$

* W_s : Fractional weight of salable matter in total matter

W_n : Fractional weight of non-salable matter in total matter

r_s : Fractional weight of carbon in salable matter

r_n : Fractional weight of carbon in non-salable matter

W_s may be broken down into W_{s1}, W_{s2}, W_{s3} -------

r_s : r_{s1}, r_{s2}, r_{s3} --------

W_n : W_{n1}, W_{n2}, W_{n3} --------

r_n : r_{n1}, r_{n2}, r_{n3} --------

Weight of Normal Matter (yield) per Unit Area: N

This term will be eliminated in the final equation. It is introduced here to explain the derivation of the equation.

I : Fractional increase

$N \times I$ = Extra matter produced by CO_2 fertilization

$N \times R$ = Carbon needed to produce normal yield

$N(1 + I)R$ = Total carbon needed to to produce the normal yield and extra yield

It is assumed that, after fertilization, even carbon needed for the production of normal yield is supplied by the CO_2 fertilizer.

$$\frac{\text{Net Increase}}{\text{carbon needed for fertilization}} = \frac{NI}{N(1 + I)R}$$

$$= \frac{I}{(1 + I)R}$$

Let $M = \dfrac{I}{(I + 1)R}$

Price of Yield to Price of Carbon: A

Price of yield is defined as the price per unit weight of yield composed of salable and non-salable products.

$$A = \frac{W_s \cdot P_s + W_n \cdot P_n}{P_c} = \frac{W_s \cdot P_s}{P_c}$$

P_s : Price of 1 kilogram salable matter

P_n : Price of non-salable matter = 0

P_c : Price of 1 kilogram carbon

W_s : May be broken down into W_{s1}, W_{s2}, ---------

P_s : May be broken down into P_{s1}, P_{s2}, ---------

So:

$$W_s P_s = W_{s1} \cdot P_{s1} + W_{s2} \cdot P_{s2} \text{ --------}$$

or:

$$P_s = \frac{W_{s1} \cdot P_{s1} + W_{s2} \cdot P_{s2}}{W_s} \text{ ---------}$$

<u>Conversion Economy: E_c</u>

It is defined as the ratio of the commercial value of net increased yield to the cost of carbon absorbed.

$$E_c = M \cdot A$$

<u>Absorption Economy: Ea</u>

It is defined as the ratio of the commercial value of net increased yield to the cost of the carbon applied (including those being absorbed and lost in wind). Let C_A represent absorption coefficient:

$$C_A = \frac{\text{C absorbed}}{\text{total C applied}} \text{ (by weight)}$$

Then:

$$E_A = M \cdot A \cdot C_A = \frac{I}{(I + 1)\ R} \quad \frac{W_s\ P_s}{P_c} \cdot C_A$$

Let $K = \frac{I\ W_s}{(I + 1)\ R}$ ------- Weight ratio

$P_r = \frac{P_s}{P_c}$ ------- Price ratio

Then: $E_A = K \cdot P_r \cdot C_A$ will be the final form for the absorption economy equation.

Chemical Analysis and Yield Weight Ratio

Past experiments have yielded little information needed in this study; therefore, field, as well as laboratory work, was conducted to collect these variables. However, only four major crops planted by the farmers in Taiwan were covered. A mere glance at the varied chemical composition and weight ratio of their final products will show that the importance of the need of a general Absorption Economy Equation is not overemphasized.

It is the author's hope that, with these data and the relevant information discussed in the next section, a rough estimate of the Absorption Economy of these four crops may be obtained under a few reasonable assumptions.

TABLE 1. The chemical composition of rice.

Composition	Unhulled Rice (%)	Straw or Dried Stalk (%)	Root (%)
Moisture	12.72	10.84	14.80
Ashes	4.60	13.82	15.20
Protein	6.74	5.13	11.34
Cellulose	9.25	27.86	23.54
Carbohydrates (starch)	64.18	40.93	28.13
Fat	2.51	1.42	6.99
Total	100.00	100.00	100.00

TABLE 2. The price and weight ratio of rice.

Name of Crop Product	Weight (%)	Price (NT$/kg.)
Unhulled rice	41.00	3.8
Straw	42.00	0.4
Root	17.00	No commercial value
Total	100.00	

TABLE 3. The chemical composition of soybeans.

Composition	Root (%)	Bean (%)	Shell (%)	Leaves & Stalk (%)
Moisture	5.96	9.25	12.00	16.00
Ashes	14.30	4.96	8.10	10.20
Protein	17.10	35.41	6.30	7.40
Cellulose	25.80	4.84	30.10	26.10
Carbohydrates (starch)	27.94	29.32	42.00	38.30
Fat	8.90	16.22	1.50	2.00
Total	100.00	100.00	100.00	100.00

TABLE 4. The price and weight ratio of soybeans.

Name of Crop Product	Weight (%)	Price (NT$/kg.)
Bean or seed	54.15	8.2
Shell	22.30	--
Leaves & stalk	19.32	--
Root	4.23	No commercial value
Total	100.00	

TABLE 5. The chemical composition of sweet potatoes.

Composition	Hair Root (%)	Sweet Potato (%)	Leaves & Stalk (%)
Moisture	6.55	75.28	88.50
Ashes	9.00	1.25	1.40
Protein	12.00	1.11	1.40
Cellulose	22.00	0.99	3.30
Carbohydrates (starch)	40.31	20.94	5.00
Fat	10.14	0.43	0.40
Total	100.00	100.00	100.00

TABLE 6. The price and weight ratio of sweet potatoes.

Name of Crop Product	Weight (%)	Price (NT$/kg.)
Hair root	4.56	No commercial value
Sweet potato	51.16	2
Leaves & stalk	44.28	0.4
Total	100.00	

TABLE 7. The chemical composition of sugar cane.

<table>
<tr><th>Composition</th><th>Root (%)</th><th>Stalk (%)</th><th>Leaf (%)</th></tr>
<tr><td>Moisture</td><td>5.18</td><td>73.50</td><td>14.64</td></tr>
<tr><td>Ashes</td><td>12.00</td><td>0.95</td><td>7.12</td></tr>
<tr><td>Cellulose</td><td>32.70</td><td>9.70</td><td>32.50</td></tr>
<tr><td>Carbohydrates (starch)</td><td>34.01</td><td>15.00</td><td>30.51</td></tr>
<tr><td>Fat</td><td>5.39</td><td rowspan="2">0.85</td><td>5.43</td></tr>
<tr><td>Protein</td><td>10.72</td><td>9.80</td></tr>
<tr><td>Total</td><td>100.00</td><td>100.00</td><td>100.00</td></tr>
</table>

TABLE 8. The price and weight ratio of sugar cane.

Name of Crop Product	Weight (%)	Price (NT$/kg.)
Root	20.68	No commercial value
Stalk (cane)	42.20	1.7
Leaf	37.12	0.1
Total	100.00	

Remarks: (1) Price and weight ratio are referred to the different crops under the same conditions as indicated in the chemical composition table.

(2) Price unit is in New Taiwan currency (NT$) per kilogram (conversion rate 1 US$ = 42 NT$, 1 kilogram = 2.2 lbs.).

Possible Carbon Source and Its Cost

As to the source of CO_2 used in CO_2 fertilization, both CO_2 in the air and in the flue gas from a power generating plant would be ideal because the only cost involved will be the equipment and handling charge. The former constitutes a source only when CO_2 exhaustion effect exists, but the flue gas may be used in the whole region of CO_2 fertilization. The only cost for obtaining these materials is the transmission cost. The cost for distributing CO_2 to the whole crop area will be discussed later. In other words, this cost covers only the transmission expenditure from source of CO_2, such as power plant to the site of application. Because the length of delivery pipe can be defined only when the size of land under one operating unit and the site of power plant is decided, and also due to the small plot generally existing in Taiwan and other densely populated countries, 1/10 of a hectare will be selected as an operating unit.

As to the CO_2 in the air used for eliminating CO_2 exhaustion, the only cost will be the expenditure to compress the air to the desired pressure of distribution. The cost for carbon in flue gas consists of: (1) transmission from power plant or from where the flue gas is generated to the site of application, and (2) purification cost, if necessary, for the elimination of harmful elements in the flue gas. The elements that should be removed will vary for different crops.

For economic reasons it is apparently necessary to locate the flue gas source as near as possible to the site of application. The efficiency of a steam power plant is reduced when its generating capacity is too low and it is also necessary to limit the size of the power plant in order to not occupy too much arable land. For the rough estimate of carbon cost needed in this research, a power plant generating enough power and CO_2 for 100 hectares of land will be selected.

Distance of Transmission

For a power plant site located at the center of 100 hectares of land, the representative distance of transmission line is equal to 1,000/2 = 500 meters, approximately.

Power Consumption

The power needed for the delivery of 15 cfm (maximum CO_2 required per 1/10 hectare (see appendix)) to a distance of 500 meters will be estimated in the following steps:

A. Determination of pipe diameter

Select V = 1,800 fpm as distribution speed, use equation

$$d = \sqrt{\frac{576\ Q}{V \times \pi}} = \sqrt{\frac{576 \times 15}{1,800 \times \pi}} = 1.235$$

use d = 1-1/4"

$$\text{Then } V = \frac{1.23}{1.25} \times 1,800 = 1.730 \text{ fpm}$$

B. Determination of pressure loss in pipe

$$P = \frac{0.03\ FL}{d^{1.24}} \left(\frac{V}{1,000}\right)^{1.84}$$ (From reference 2, p. 433)

F = factor for roughness (for average pipe F = 1)

L = lengh of pipe, ft.

d = diameter of pipe, in.

P = pressure loss, in. of water

V = velocity in pipe, fpm

Then:

$$P = \frac{0.03 \times 1 \times 500 \times 3.3}{(1.25)^{1.24}} \times \left(\frac{1,780}{1,000}\right)^{1.84}$$

$$= 49.5 \times \frac{1.78^{1.84}}{1.25^{1.24}} = 108 \text{ in. water}$$

C. Total air horsepower

ahp = 0.000157 pav. (From reference 2, p. 392)

$$= 0.000157 \times 108 \times \frac{\times 1.24^2}{4 \times 144} \times 1,780 = 0.25$$

Actual ahp = ahp/eff. = 0.25/0.65 = 0.38 (eff. from p. 538, ASHVE Guide, 1945)

D. CO_2 delivered (cu. ft. per hr.) versus power consumption

Q = 15 x 60 = 750 cu. ft.

Power consumption = 0.38 Hp-hr. = $\frac{0.38}{1.341}$ = 0.28 kilowatt-hour

E. Carbon delivered by 0.28 kw-hr.

$$= \frac{750}{8.545} \times \frac{12}{44} \text{ lb.} = 24 \text{ lb. or } 11 \text{ kg.}$$

(1 lb. carbon dioxide at 60°F. = 8.545 cu. ft.)

F. Power cost for each kg. carbon transported to distribution site

0.28 kw-hr. x NT\$ 0.4 (US\$ 0.01)/11

= 0.011 NT\$/kg. or 0.00028 US\$

Pipe and Installation Cost for 500 Meter 1-1/4" Ø Steel Pipe

250 US$ = 10,000 NT$ (Asia Pipe Manufacturing Company, Taipei, Taiwan)

Interest and Depreciation Cost per kg Carbon

Carbon delivered per year (actual need of 1/10 hectare)

= 11 kg/hr x 8.5 hr/day x 180 days/year

= 16,830 kg or 16.8 tons

Life of pipe = 20 years

Interest = 5% annual

Straight line formula is used for the calculation of interest

Salvage value of pipe = 10% original cost

$\frac{250 \times 90\%}{20}$ = US$ 11.2 ---------- annual depreciation

$\frac{(250 \times 1.1)}{2} \times \frac{5}{100}$ = US$ 6.85 -- annual interest

Total cost per kg of carbon

= power cost + depreciation cost + interest

= 0.00028 US$ + $\frac{11.2}{16,800} + \frac{6.85}{16,300}$

= 0.00028 + 0.00109 US$

= 0.00137 US$ or 0.055 NT$ per kg carbon

Application of Absorption Economy Equation to Rice Crop

Equation

$$E_A = K \cdot P_r \cdot C_A$$

Assumption

All carbohydrates, fat, protein, cellulose are assumed to have $C_6H_{12}O_6$ structure for calculation. In view of other unknowns, this assumption should be precise for this study.

$$\text{Carbon in } C_6H_{12}O_6 = \frac{72}{72 + 12 + 96} = \frac{1}{2.5}$$
(fraction of total)

Calculation of r_s and r_n

$$r = \frac{100 - (\text{moisture} + \text{ash})}{2.5} \times \frac{1}{100}$$

$$r_{s1} \text{ (unhulled rice)} = \frac{100 - (12.74 + 4.60)}{2.5} \times \frac{1}{100} = 0.33$$

$$r_{s2} \text{ (straw)} = \frac{100 - (10.84 + 13.82)}{2.5} \times \frac{1}{100} = 0.30$$

$$r_n \text{ (root)} = \frac{100 - (14.80 + 15.20)}{2.5} \times \frac{1}{100} = 0.28 \text{ or } 28\%$$

Calculation of R

$$R = \frac{\sum W_{si}\, r_{si} + \sum W_{ni}\, r_{ni}}{1}$$

$$= \frac{0.41 \times 0.33 + 0.42 \times 0.30 + 0.17 \times 0.28}{1}$$

$$= 0.308$$

Calculation of K (for varying I)

$$K = \frac{I\, W_s}{(I + 1)\, R}$$

For I ranging from 0.7 to 1.5 K values are listed in Table 9.

TABLE 9. K values for rice crop.

I	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5
K	1.11	1.19	1.27	1.34	1.41	1.47	1.52	1.57	1.61

Calculation of P_r

$$P_s = \frac{P_{s1}\,W_{s1} + P_{s2}\,W_{s2} + \text{---}}{W_s} = \frac{0.41 \times 3.8 + 0.42 \times 0.4}{0.83} = 2.15$$

$$P_r = \frac{P_s}{P_c} = \frac{2.15}{0.055} = 39$$

Absorption Economy

$$E_A = K \cdot P_r \cdot C_A = 1.41 \times 39 \times 0.5 = 27.5$$

for $K = 1.41$ and $C_A = 0.5$

Values for the Various Absorption Economy Equation Parameters

TABLE 10. V_n, V_s, W_s, P_s, and P_r values for four Taiwan crops.

Crop	Constituents of W_s	W_s	r_s	r_n	R	P_s	P_r
Rice	Unhulled rice, straw	.83	.31	.28	0.303	2.15	39
Soybean	Bean	.54	.34	.32	0.332	3.2	150
Sweet potato	Potato, leaf and stalk	.95	.06	.33	0.080	1.21	22
Sugar cane	Cane, leaf	.79	.20	.31	0.242	0.95	17

TABLE 11. K values for four Taiwan crops.

Crop	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5
Rice	1.11	1.19	1.27	1.34	1.41	1.47	1.52	1.57	1.61
Soy-bean	0.67	0.72	0.77	0.81	0.85	0.89	0.92	0.95	0.97

TABLE 11 (continued)

Crop	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5
Sweet potato	4.88	5.27	5.62	5.92	6.21	6.46	6.68	6.90	7.12
Sugar cane	1.34	1.45	1.54	1.62	1.71	1.78	1.84	1.90	1.95

A Nomogram for the Solution of Absorption Economy Equation

For a general solution of the absorption economy equation, a nomogram (Figure 2) was constructed and it will save the drudgery of tedious calculation for every individual set of data. Nevertheless, due to the large variation of parameter data between different crops and the endeavor of using large scale to cover maximum range, this nomogram will produce only an approximate answer. For more accurate results, at least one nomogram should be constructed for every crop.

The Absorption Economy for Four Crops in Taiwan

For C_A ranging from 10 per cent to 50 per cent and I from 0.7 to 1.5, values of absorption economy range for four Taiwan crops are tabulated in Table 12.

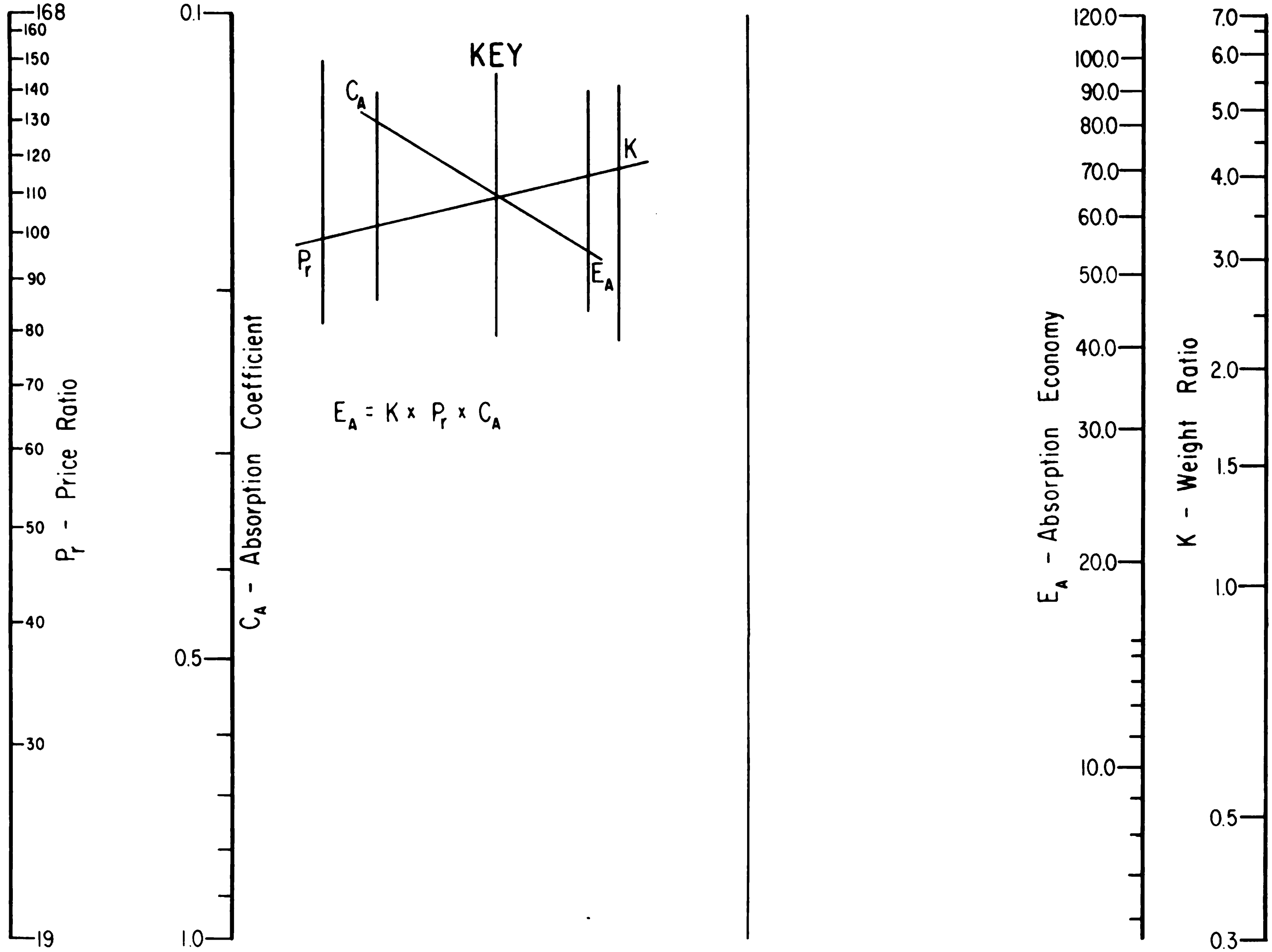


Figure 2 Absorption Economy

TABLE 12. The absorption economy range for four Taiwan crops.

Crop	Absorption Economy Range ($E_A = K \cdot P_r \cdot C_A$)	
	Lowest	Highest
Rice	4.35	31.40
Soybean	10.15	72.80
Sweet potato	10.70	78.40
Sugar cane	2.27	16.50

It may be tentatively concluded from the data in Table 12 that under reasonable (conforming to the past experiment results) conditions, CO_2 fertilization, judging by its absorption economy alone (excluding CO_2 distribution cost), is a highly profitable practice. Nevertheless, its real value has to be re-evaluated when the estimation of the distribution cost in the field is available. Results obtained so far encourages further investigation.

FACTORS AFFECTING THE ABSORPTION COEFFICIENT FOR DIFFERENT CROPS IN DIFFERENT STAGES OF GROWTH

The age and type of a plant will require different methods of administering CO_2 fertilization. Two extreme cases will be dealt with here.

1. Plants with prowling stalk and plants in their early age of growth (hereafter referred to as Type I crop).

2. Tall plants planted in rows with abundant leaves (Type II crop).

For the Type I crop, it is desirable to enrich the air from ground up to a desired height since plants do not offer any wind braking power and also leaves are so scarce that absorption power is low. It is mandatory to design some wind break to keep diffusion loss low to reduce CO_2 gradient if plants are not in a greenhouse. As to the second type, the design will try to distribute CO_2 near the ground. Because plants are thick enough to act as a good wind break, blowaway loss is negligible and also any CO_2 before diffusing to the upper air must pass through many leaves which possess a very great absorption power as mentioned in the Literature Review. The second type is much better as far as the prevention of CO_2 loss design is concerned. The following discussion will be mainly concerned with Type I crop.

Carbon Required to Enrich a Definite Volume of Air

It is very important to know how much carbon is needed to enrich a definite volume of air to a specified concentration. If this is too much, then even the leaf absorption power is high, the daily carbon requirement in the beginning of each enrichment will render this method unpractical. An equation is developed below for this purpose.

Q : Daily carbon requirement to bring CO_2 in air to the desired concentration in kg/ha.

B : Degree of enrichment above normal (normal air 100%). If enrichment is three times normal CO_2, then B = 2.

H : Height of enrichment (= height of crop at application time) in meter.

K : Constant kg/m-ha

$Q = K \cdot B \cdot H$

(k = 1.7 kg/m-ha based on 10^4 liter air contains 1.7 gram carbon)

$Q = 1.7\ B \cdot H$

An alignment chart (Figure 3) is developed for varying B and H and this chart is very indispensible in view of the constant changing of height of crops and their specific reaction to different levels of CO_2 concentration.

Diffusion Loss

In view of the difficulties encountered by the past investigators in glass houses, this analysis will be based on an open field application instead of a closed compartment method. Diffusion rate or loss from the enriched air to the

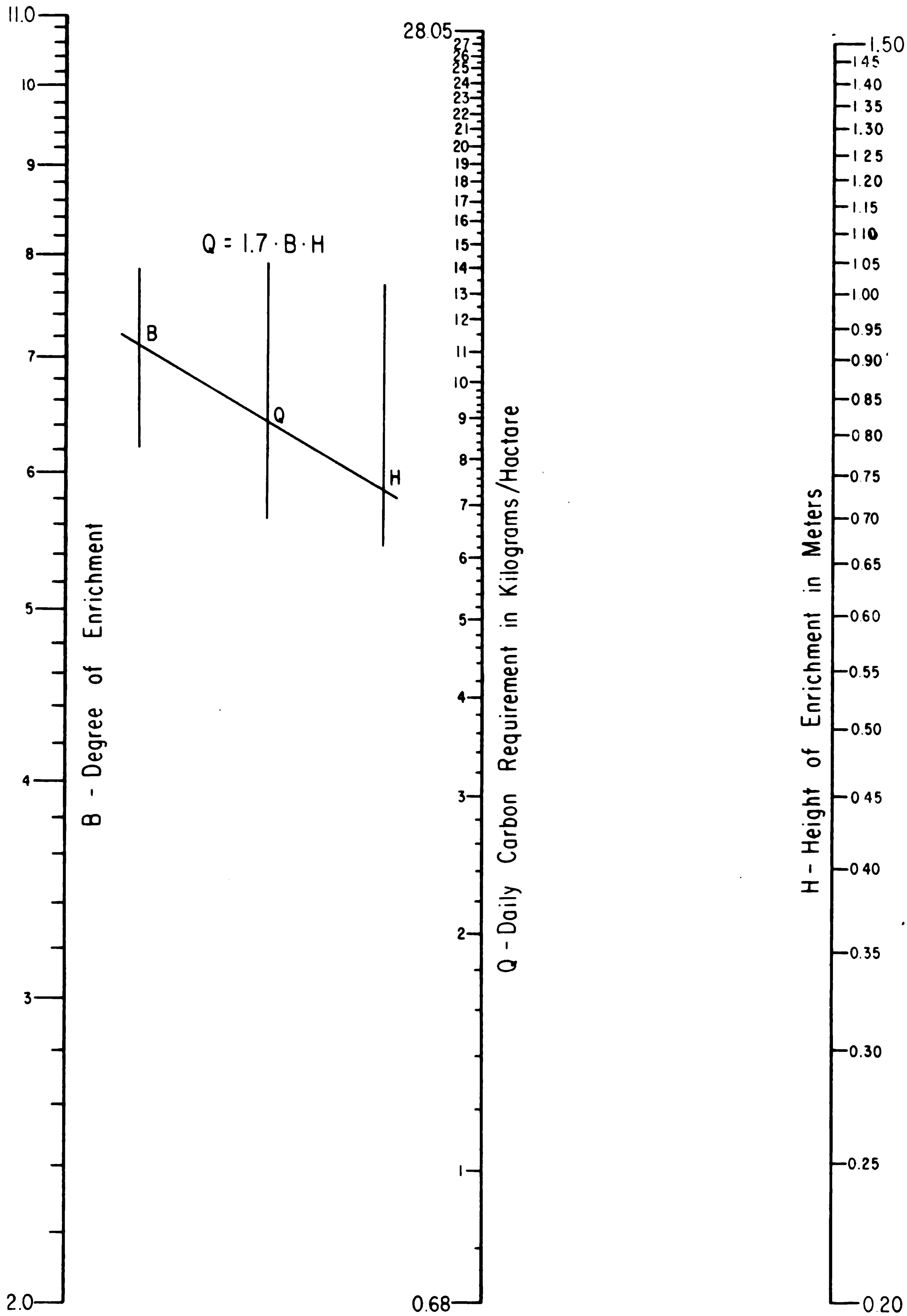
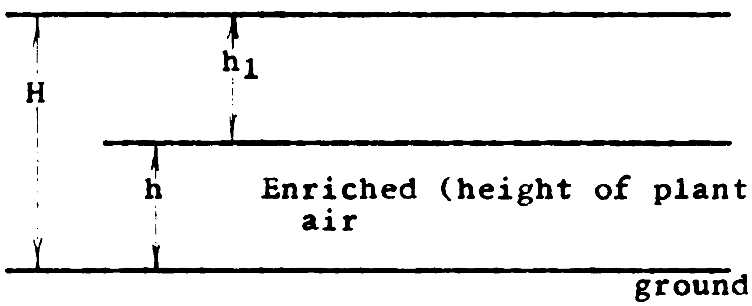


Figure 3 Daily Carbon Requirement

natural will be a major factor to determine the feasibility of open air application to Type I crops. The choice between a glass house and an open field or the chance of bringing about a successful CO_2 fertilization method for Type I crops to ordinary farming hinges mainly on this factor. Symbols to be used are illustrated in the following diagram to prevent ambiguity.



Also two assumptions are made as follows:

1. When CO_2 diffuses out of height h (approximately the height of crop), it is considered a loss.

2. Normal CO_2 concentration above height H.

Diffusion rate of free gases depends on the nature of the gases, the temperature, the total pressure, and linear rate of variation of the partial pressure of each gas. The diffusion constant used by Edgar Buckingham in the investigation of CO_2 diffusion through soil will be adopted for this analysis. Diffusion constant is defined as average number of cubic centimeters of each of two gases which would, in one second, pass in opposite directions through one cm^2 of cross-section at a specified partial pressure gradient mm/cm. Since the concentration of CO_2 in CO_2 fertilization work will be expressed in percentage of volume of air and also partial pressure is proportional to the amount of gas present, the unit "volume per cent of CO_2 in air per centimeter" will be used to replace the commonly used gradient unit mm/cm.

Let D_L = Diffusion loss of carbon in kg/ha-hr

K = Diffusion rate of CO_2 (2.16, according to Buckingham) cm^3 per cm^2 per sec. at 0.13%/cm (= 1 mm/cm partial pressure gradient) at temp. = 27°C. P = 760 mm Hg

G = Gradient of CO_2, then in %/cm

$$D_L = 2.16 \times 10^{-4} \quad \frac{G}{0.13\%/cm}$$

$$h_1 = H - h$$

α = Desired enrichment in fraction of air by volume

h = The distance from the upper surface of enrichment to the ground surface in meter

$$D_L = 2.16 \times 10^{-4} \frac{(\alpha - 0.03\%)}{0.13\%/cm \times h_1 \times 100} \; (cm^3/cm^2 - sec)$$

$$= \frac{2.16\ (\alpha - 0.0003)}{10^4 \times 0.0013 \times h_1 \times 10^2} \times \frac{10^8 \times 3600}{10^3} \quad (\text{liters } CO_2/\text{ha-hr})$$

$$= \frac{2.16 \times 3600}{10 \times 0.0013} \times \frac{(\alpha - 0.0003)}{h^1} \times \frac{1}{22.4} \times 12 \times \frac{1}{10^3} \; (\text{kg carbon/ha-hr})$$

$$= 320.4 \times \frac{(\alpha - 0.0003)}{h_1} \quad (\text{kg carbon/ha-hr})$$

An alignment chart (Figure 4) for varying h_1 and α is also developed.

The Absorption Power of Leaf

See Literature Review for discussion on this topic.

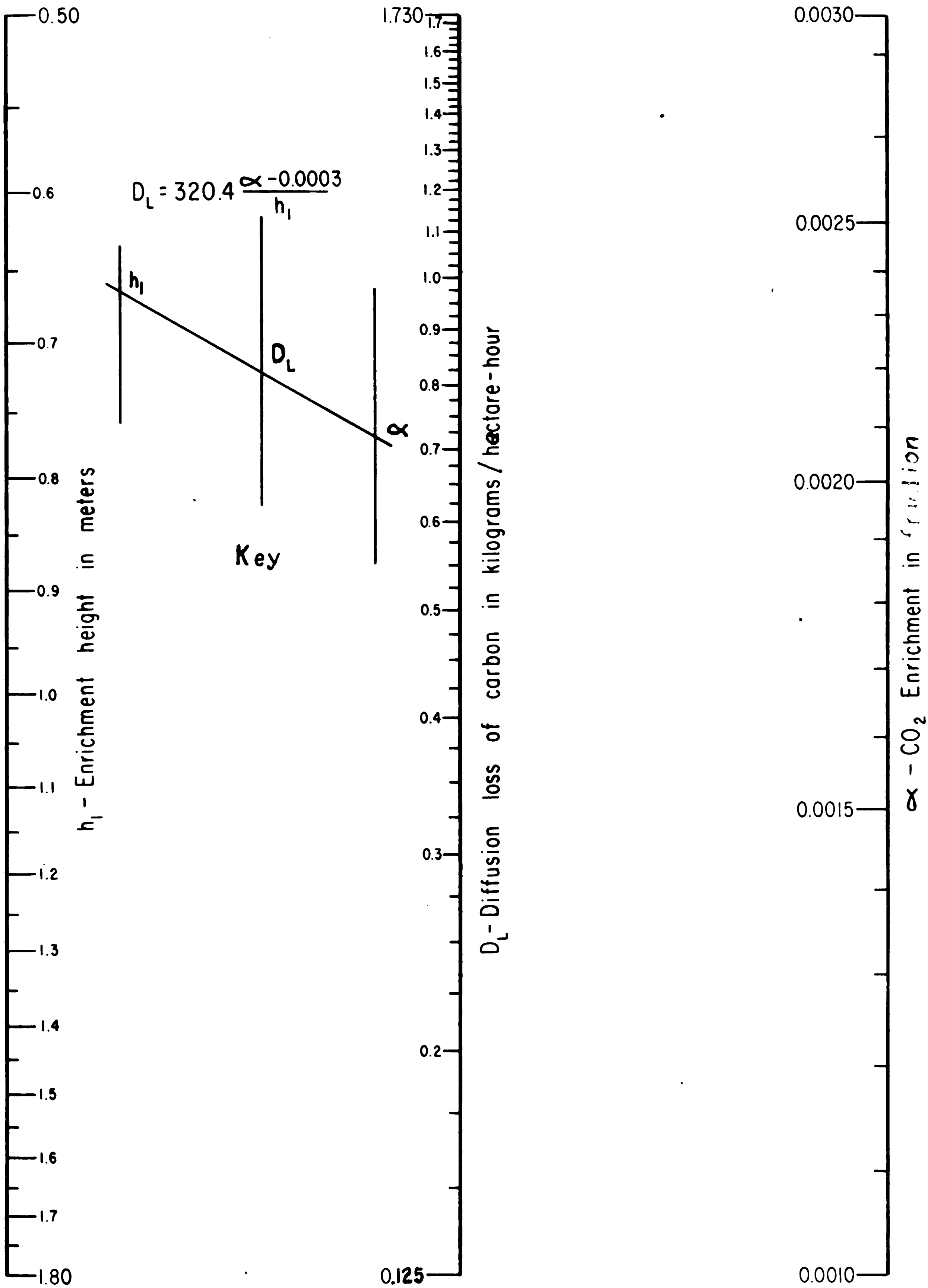


Figure 4 Diffusion Loss of Carbon

Height of Plants and the Releasing Point of CO_2

Refer to the introduction of this section for discussion on this point.

Although these factors have been considered together in this section, nevertheless they carry different weight in the two different systems. The first two factors are important in the system for Type I crop and the last two are important for Type II crop. Type I needs a windbreak fence and Type II has no such need. In view of the majority of crops belonging to Type II category and the huge labor consumption for putting and taking down a windbreak fence in a large area, the design to be discussed will be based on Type II crop. However, the distribution system will be similar in the two different types; therefore, it is reasonable to expect that the design system will be also applicable to Type I crop.

DESIGN OF A CARBON DIOXIDE DISTRIBUTION SYSTEM FOR TYPE II CROP

Based on the previous analysis of absorption economy, a rough conclusion may be reached that carbon dioxide fertilization is profitable only when a proper method of controlling such economy parameters as C_A, P_r, etc. is available. Hence, this design will try to keep these parameters within profitable range.

Since the size of most plots of oriental farms are 1,000 square meters approximately, the operating unit size will be selected accordingly for this design. However, the design may be enlarged for larger size field plots with little difficulty. Also, as the plants absorb carbon only in the CO_2 gas phase, it is no question that carbon must be converted into carbon dioxide gas before being distributed to the plants. Due to the fact that carbon dioxide may be generated on the farm as well as in a central plant, the decision in this respect is again a matter of economy.

From the foregoing economy analysis, it is apparent that carbon fertilization is only practical when carbon could be supplied at a considerably lower price in contrast to the price of average farm yield. Although carbon price is already considerably lower than most of the farm yield, it would be even lower and more desirable if its energy could be utilized first and then only the valueless carbon dioxide exhaust gas is collected for supplying the crops as a fertilizer. This method of obtaining carbon dioxide obviously has a definite advantage to the one of burning coal at the field, which wastes its valuable heat energy while energy is definitely needed for distributing carbon dioxide.

Fortunately most densely populated countries for which this system is designed are expanding their industry and are badly in need of more electric power. Coupling these two needs into one project by building thermo-electric power plant with carbon dioxide collecting equipment will lower both the cost of electricity and carbon dioxide fertilizer. In view of this possibility, the proposed design will use ready-made carbon dioxide gas from power plants as the carbon dioxide source.

Considering the transmission cost of carbon dioxide from the source to the point of application, the power plant should be located as near to the farm as possible. But a moderate-sized power unit has to be selected on account of the extremely low efficiency of a very small capacity power plant.

In addition to the few design principles explained above, many other assumptions have to be made because this project is such a new one in nature that not a single paper is available. However, the assumptions based on relevant researches conducted in other scientific domains will lie within reasonable range so that conclusions may be in the right direction and easy adjustment of the design also may be easily made to accommodate local situations deviating from the assumptions.

Furthermore, economy parameters discussed before vary from one place to another due to especially biological and climatic differences and their interaction. Hence, the field experiment will have to wait until the author returns to his country and final proof of the conclusions reached in this study secured. However, this design will help pin down the carbon dioxide distribution cost and achieve the objective of this study which is indispensible in the beginning stage of this type research.

The general design specifications are listed below:

1. Operating Unit: 1,000 square meters
   20 by 50 meter rectangular shape

2. Type of Crop: Any Type II crop or plants with upright stalk and medium amount of leaves

3. Maximum Supply of CO_2: 15 cubic feet per minute per 1,000 meter square (rice is used as the plant for estimation, see Appendix)

4. Releasing Point of CO_2: Near the ground surface and as low as possible

In addition to the demand for a greater throw of carbon dioxide efflux discharged by the releasing outlet for the maximum coverage of plants by each single hole, there are many other factors, such as entraining ratio, angle of spread *et al*. which will affect the economy of carbon dioxide fertilization too. They are the major parameters which deserve consideration in the design. Since ventilation engineers have done considerable work similar in nature, their terminology with a little modification will be adopted in this study and the definitions are given below:

1. Throw: The horizontal distance an air stream travels on leaving the outlet to a position at which air motion reduces to a maximum velocity of 50 feet per minute.

2. Spread: The divergence of the air stream in a horizontal or vertical plane after it leaves the outlet.

3. Terminal velocity: The average air stream velocity at the end of the throw.

4. Drop: The vertical distance, the lower edge of the air stream drops between the outlet and the end of its throw.

5. Rise: The converse of drop.

6. Aspect ratio: The ratio of the length to the width of the outlet.

7. Induction: The entrainment of free air by an air stream.

8. Total mixture: The mixture of carbon dioxide discharged from outlet and free air.

9. Induction ratio: The total mixture divided by the primary air stream (carbon dioxide mixture).

Also, in addition to the adoption of the terminology, their data and relevant formulas are used freely to design a carbon dioxide design procedure or method, but the fitness of each formula or information used remains to be proven at later experiments. Nevertheless, these valuable formulas will help tremendously in the beginning of this study even if, at a later time, discrepancy should be discovered. Without them, no one would know how to start to design and the man trying to do any research on this topic would be left in a real vacuum. The carbon dioxide distribution design study will be done in the following sequence:

A. Develop a lateral pipe arrangement, outlet diameter, outlet spacing, and mixture (CO_2 and air) design procedure.

B. Develop a lateral pipe and main pipe pressure, friction, and horsepower calculation procedure.

C. Application of these design procedures in a 20 by 50 meter rice field.

Develop a Lateral Pipe Arrangement, Outlet Diameter, Outlet Spacing, and Mixture Design Procedure

Throw Formula

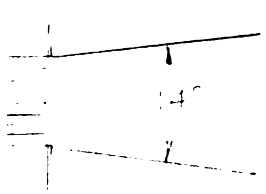
$$L = 0.62 \frac{Q_c}{\sqrt{A_1}}$$ (from ASHVE Guide, 1949, p. 788)

L : Throw, ft.

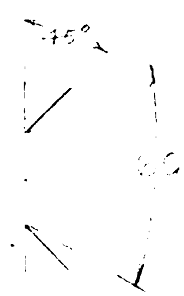
A_1: Effective outlet area (free area x discharge coefficient), in.^{2}

The use of this formula is limited only to straight flow outlet with aspect ratio less than 16 and the discharge coefficient is approximately 0.8. Also rice is planted in check rows with the conventional 10 in. by 10 in. space between plants.

Spread of Air Stream from Two Different Type Outlets



Straight Outlet



Diverging Outlet

Vertical Drop and Rise Formula

$$H_1 = L \times \tan \left(\frac{\text{spread angle}}{2}\right)$$

H_1 : Drop due to spread (air stream temperature at same temperature as free air), ft.

L : Throw, ft.

When there is a temperature difference between the carbon dioxide stream and free air, then use the following equation to find the additional drop.

$$H_2 = \frac{n_1 \, (t_r - t_{as}) \, L^{n2}}{V_1}$$

H_2 : Additional drop due to temperature difference, feet

n_1 and n_2: Constants (suggested values for $n_1 = 5$ and $n_2 = 1.2$)

t_r : Free air temperature, degree F

t_{as} : Carbon dioxide stream temperature, degree F

v_1 : Jet or efflux velocity, feet per minute

Total vertical drop or rise = $H_1 + H_2$

From these formulas and data quoted above, the following design procedure is developed.

Known Quantity

Q_c : Carbon dioxide required in cfm per 1,000 square meters

V_m : Maximum outlet allowable discharging stream velocity, ft. per minute

Design Procedure

1. Select throw and lateral arrangement in accordance with field plot shape. It is better to mount the laterals along the longer sides of the field plot and keep a

minimum number of lateral pipe in the field. But too large a throw generally require large discharge quantity even the carbon dioxide requirement is low, therefore, more power consumption. It is a matter of compromise.

2. Use chart in Figures 5 and 6 to find spread.
3. Calculate the projection area of the stream from a discharge outlet.

   Projection area = 1/2 L x spread, meter square

4. Calculate the number of discharge outlets needed for a definite area.

   $$N = \text{No. of outlet} = \frac{\text{total area to be covered, sq. meter}}{\text{projection area of each outlet, sq. meter}}$$

5. Calculate the net quantity of carbon dioxide to be discharged by each outlet.

   $$Q_n = \text{Discharge quantity by each outlet} = \frac{Q_c}{N}$$

6. Select trial values for discharge outlets dimensions which will keep discharging velocity smaller than V_m (varies according to crops) and still delivers the required Q. The narrowest optimum slot outlet shape is preferred for its ability to obtain high entrainment ratio and therefore better mixing of carbon dioxide and fresh air. Let A be its area.
7. Find the effective discharge area of each outlet

   A_e = the effective area of an outlet = A x 0.8

8. Use the formula:

   $$Q = \frac{L \times \sqrt{A_1}}{0.82}$$

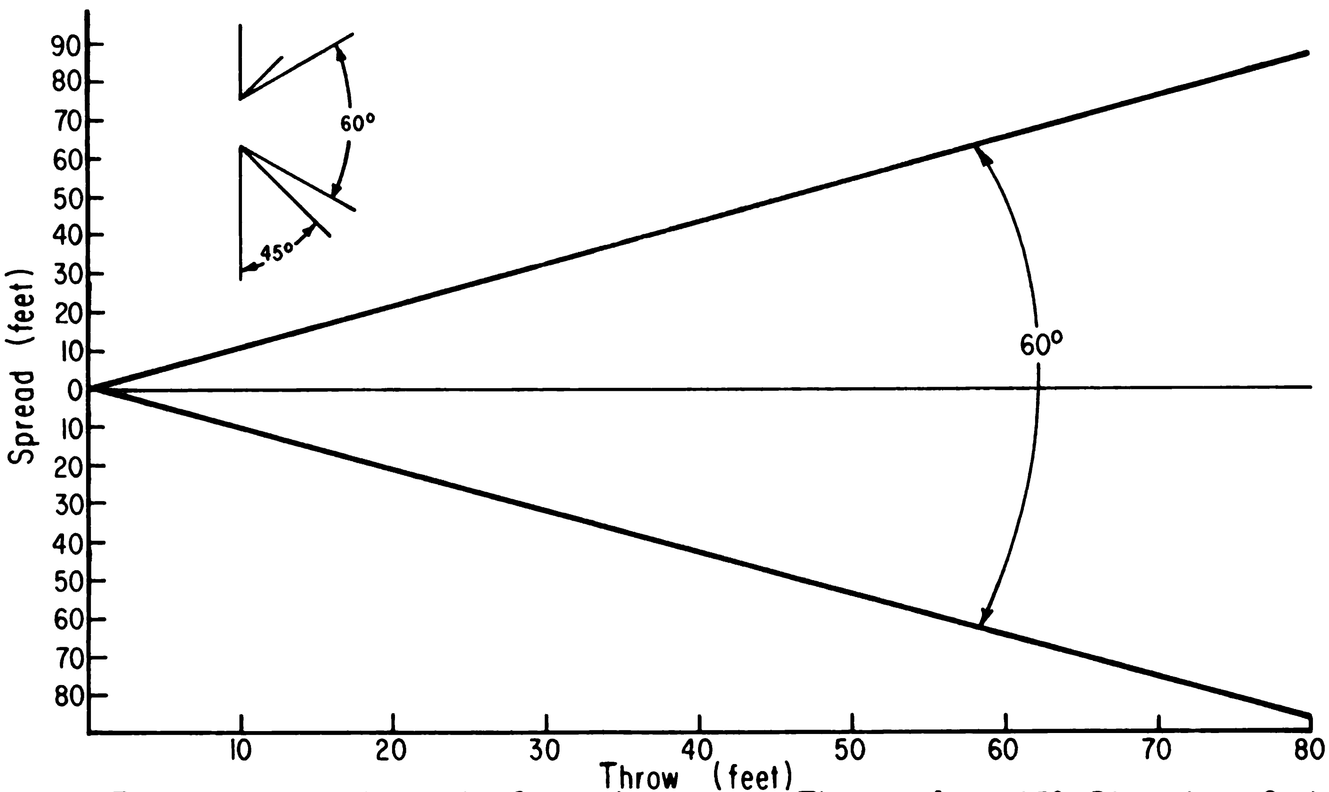


Figure 5 Horizontal Spread versus Throw for 45° Diverging Outlet

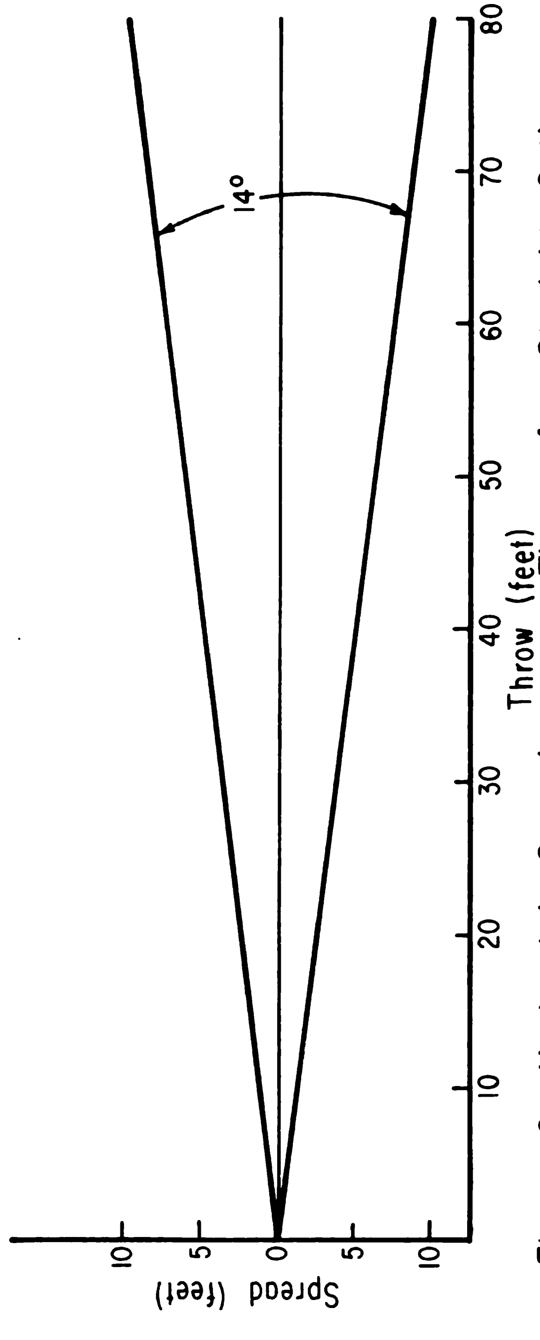


Figure 6 Horizontal Spread versus Throw for Straight Outlet

to find the actual quantity of carbon dioxide and air mixture discharged by each outlet.

9. Check actual velocity of discharge efflux against V_m.
10. Calculate the actual mixture ratio by using Q_n and Q obtained in (5) and (8) and check against the desired mixture ratio which should be smaller than Q_n/Q.
11. Make a lateral pipe arrangement drawing.

Develop a Lateral Pipe Pressure, Main Pipe Pressure, Pipe Friction, and Air Horsepower Calculation Procedure

The successful evaluation of these variables depends on the proper selection of optimum flow velocity in the pipes, which could only be decided after a laborious test. For the present work values recommended by ventilation engineers for air condition work will be adopted, but for future Carbon Dioxide Fertilization Engineering work new experiments should be conducted. Values recommended by the ventilation engineers are listed below:

Description	Maximum Velocity in fpm
Main pipe	1,300 - 2,200
Lateral pipe	1,000 - 1,800

Calculation Procedure

1. Selection of lateral and main pipe size.

Determine lateral and main pipe flow according to the pipe arrangement drawing and substitute these flow data into the following formula.

$$d = \sqrt{\frac{576Q}{V}}$$

d : Size of lateral or main pipe diameter, in in.

V : Recommended flow velocity in the pipe, in fpm

Q : Flow in pipe, in cfm

2. Determine the minimum pressure in the lateral pipe.

$$V = 4{,}005 \sqrt{H_w}$$

V : Recommended flow velocity, fpm

H_w : Minimum pressure in the lateral pipe, in inches of water

3. Calculation of input pressure or pumping pressure to insure desired flow rate and discharge velocity at the farthest outlet. Use the following formula to find friction loss both in the main and lateral.

$$P_f = \frac{0.03\ FL}{d^{1.24}} \left(\frac{V}{1{,}000}\right)^{1.84}$$ (From Heating and Air Conditioning, p. 433, by John K. Allen, *et al*.)

P_f : Pressure loss due to friction, in in. of water

F : Factor for roughness (F = 1 for average pipe)

L : Length of pipe, in feet

d : Diameter of the pipe, in inches

V : Velocity of flow in pipe, in fpm

then, Pumping or input pressure = minimum pressure in the lateral + friction pressure loss

4. Air horsepower calculation

$$Ahp = \frac{pav \times 144}{12 \times 2.31 \times 33{,}000} = 0.000157\ pav$$ (From Heating and Air Conditioning, p. 392)

Actual Ahp = Ahp/eff.

p : Pumping pressure, in in. of water

a : Cross sectional area of pipe, in square feet

v : Flow velocity in fpm

Application of the Design Procedures to a 20 by 50 Meter Rice Field

Q_c = 15.3 cfm/1,000 meter^2

V_m = 7,900 fpm (this is the core velocity of the discharge stream which will not hit the rice plants. The average velocity = 1/3 x 7,900 fpm = 30 mph. Rice can have a normal growth at wind speed about 30 mph at least. Further experiments are needed to discover the exact V_m for different plants.)

Part A

1. Throw selected = L = 33.3 ft. or 10 meters

2. S = 8.2 ft. or 2.5 meters

3. Projection area = 1/2 x 8.2 x 33.3

   = 136 ft.^{2} or 12.5 m^2

4. $N = \dfrac{1000}{12.5} = 80$

5. $Q_n = \dfrac{Q_c}{N}$

   $= \dfrac{15.3}{80} = 0.191$ cfm

6. Try 3" x 1/4" outlet (aspect ratio = $\dfrac{3}{1/4} = 12$)

   A = 3 x 1/4 = 0.75 in.^{2}

7. $A_1 = 0.8 \times 0.75 = 0.6$ in.^{2}

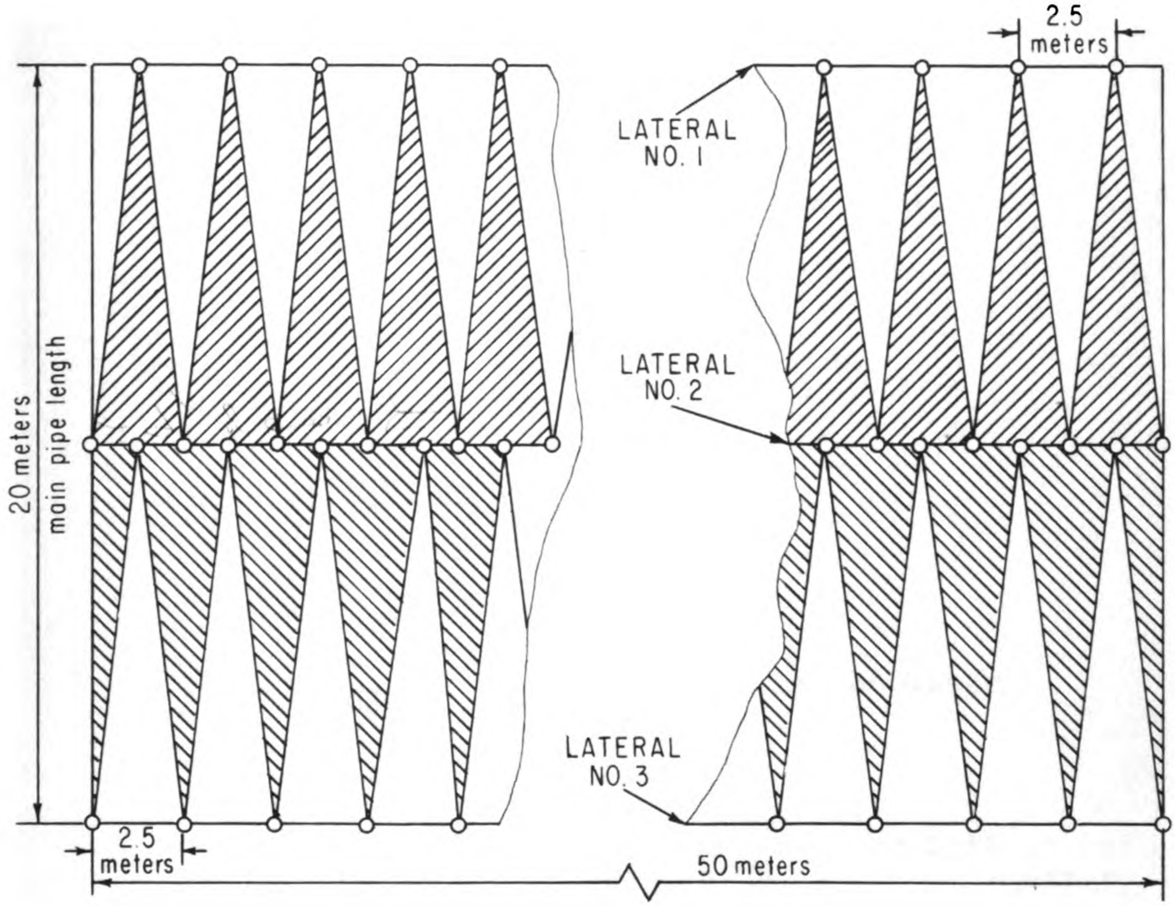
8. $Q = \dfrac{L \times \sqrt{A_1}}{0.82} = \dfrac{33.3\sqrt{0.6}}{0.82} = 31.4$ cfm

9. Actual discharge velocity =

   $\dfrac{31.4 \times 14.4}{0.6} = 7{,}550$ fpm (< 7,900 fpm)

10. $\dfrac{Q_n}{Q_c} = \dfrac{0.191}{31.4} \times 100 = 0.61\%$ (> 0.1% which is the desired enrichment)

11. See Figure 7 for lateral arrangement.



Covered by lateral No. 1 drain

" " " No. 2 "

" " " No. 3 "

o Discharge outlet

Discharge	outlet	spacing	2.5 meters
"	"	number	8 per 100 meters^2
"	"	size	3" x $\frac{1}{4}$" slot
"	"	pressure	3.57 inches water
"	"	Q	31.4 cfm

Figure 7 Lateral Pipe Arrangement for 20 x 50 Meter Rice Field

Part B

1. Q_1 = Flow in lateral No. 1 = 20 x 31.4

= 628 cfm

Q_2 = Flow in lateral No. 2 = 40 x 31.4

= 1,256 cfm

Q_3 = Flow in lateral No. 3 = 20 x 31.4

= 628 cfm

V = 1,800 in the lateral pipe

$$d_1 = \frac{628 \times 576}{1800 \times} = 8''$$

$$d_2 = \frac{1256 \times 576}{1800 \times} = 11''$$

$$d_3 = \frac{628 \times 576}{1800 \times} = 8''$$

2. $$H_w = \left(\frac{V}{4005}\right)^2 = \left(\frac{7550}{4005}\right)^2 = 3.57 \text{ in. of water}$$

3. Pressure loss in No. 1 lateral

$$P_1 = \frac{0.03 \times 1 \times 33.3 \times 5}{8^{1.24}} \left(\frac{1800}{1000}\right)^{1.84} = 1.11 \text{ in. of water}$$

Pressure loss in No. 2 lateral

$$P_2 = \frac{0.03 \times 1 \times 33.3 \times 5}{11^{1.24}} \left(\frac{1800}{1000}\right)^{1.84} = 0.75 \text{ in. of water}$$

Pressure loss in No. 3 lateral

P_3 = 1.11 in. water

Pressure loss in main pipe

$$P_{main} = \frac{0.03 \times 1 \times 33.3 \times 2}{8^{1.24}} \left(\frac{1800}{1000}\right)^{1.84} = 0.445 \text{ in. water}$$

(for main pipe length see Figure 7)

P_f = 1.11 + 0.75 + 1.11 + 0.445

= 3.415 in. of water

Pumping pressure p = 3.415 + 3.57 = 6.985 in. water

4. $$\text{Ahp} = \frac{pav \times 144}{12 \times 2.31 \times 33{,}000}$$

$$a = \frac{\left(\frac{\pi \times 8^2}{4}\right) + \left(\frac{\pi \times 8^2}{4}\right) + \left(\frac{\pi \times 11^2}{4}\right)}{144} = 1.3 \text{ ft.}^2$$

p = 6.985 in. of water

v = 1800 fpm

Ahp = 2.57 hp or 1.9 kw

Actual ahp = 1.9/0.65 = 2.92 kw

ECONOMIC ANALYSIS OF CARBON DIOXIDE FERTILIZATION

The economy of carbon dioxide fertilization depends on absorption economy and distribution cost. For this analysis the term "distribution economy" is introduced and defined as "the ratio of carbon price of each kilogram to the cost of transporting one kilogram carbon to the immediate vicinity of plant leaves plus carbon original cost." Let E_D represent it. For further analysis, another term "fertilization economy" is also defined as "the profit or net return for each unit investment of carbon" and using the terms discussed before, this fertilization economy may be defined mathematically as:

$$E_F = E_A \times E_D$$

while

$$E_D = \frac{\text{carbon price per kg.}}{\text{distribution cost per kg + carbon price per kg}}$$

It is the author's belief that absorption economy is governed mainly by the biological parameters, such as leaf absorption power, light effect on the rate of photosynthesis, etc. The distribution economy is governed solely by the design of distribution system, which will improve tremendously after more new engineering principles and technology could be introduced in this study. Therefore, they are treated separately so that the improvement of one will not change the data obtained painstakingly for another. Also, the author believes that the carbon price and grain price will remain unchanged for quite a long time and this will make the data obtained for absorption economy valid for a long time.

Since one of the main objectives of this study is to analyze the economical possibility of carbon dioxide fertilization, E_p will be estimated on the proposed distribution system.

Cost Analysis of the Proposed Distribution System

Equipment Cost

4 hp, 3 phase motor	NT$ 2,000.00
Fan 2,512 cfm	2,000.00
Air duct or pipe	
8" diameter, 100 meters	825.00
11" diameter, 50 meters	565.00
	Total NT$ 5,390.00

Power Cost per Kilogram Carbon

Actual air hp = 3.96 horsepower or 2.92 kilowatt

CO_2 delivered per hour in cubic foot = 15 cu. ft/min. x 60 min/hr = 750 cu. ft. per hr.

Carbon delivered per hour = 11 kg.

Power cost per kg. carbon = 2.92 x 0.4/11 = 0.106

(For calculation details, see Absorption Economy section.)

Note:

1. Electric power 0.4 NT$ per kilowatt-hour
2. One NT$ equivalent to 0.025 US$

Interest and Depreciation of Equipment

Annual carbon distributed by the system

= 11 kg./hr. x 8.5 working hour/day x 180 days/year

= 16,830 kg./year

Life of equipment = 20 years

Annual interest = 5%

Straight line formula

10% salvage value

Annual depreciation = $\frac{\text{NT\$ } 5,390 \times 90\%}{20}$ = NT$ 242.00

Annual interest = $\frac{\text{NT\$ } 5,390 \times 1.1}{2} \times \frac{5}{100}$ = NT$ 148.00

Maintenance cost = NT$ 5,390 x 3% = NT$ 161.00

Total fixed cost per kg. carbon =

$\frac{\text{NT\$ } 242 + \text{NT\$ } 148 + \text{NT\$ } 161}{16,800 \text{ kg.}}$ =

0.0326 NT$/kg.

Total Distribution Cost per Kg. Carbon

D_c = 0.106 NT$ + 0.0326

= 0.138 NT$/kg. carbon

Fertilization Economy

$$E_F = E_A \times \frac{0.055}{0.138 + 0.055} = 0.285\ E_A$$

or at $E_F = 1$ (the breakeven point of fertilization practice)

E_A should be equal to 3.5.

Note: 1. 0.055 (see pages 24 and 25 for details) is the carbon price in NT$ per kg. carbon.

2. 0.138 is the distribution cost in NT$ per kg. carbon.

With proper knowledge of absorption economy, it is possible to estimate fertilization economy now for each individual crop. The conclusion will be given in the next chapter.

CONCLUSION AND RECOMMENDATION

The results of calculations based on the previous experiments tend to prove that carbon dioxide fertilization, at least for the densely populated regions, is a highly profitable practice, which promises a reasonable solution for the food crisis in the region where population has outgrown the land resource. This general conclusion was based on the following secondary conclusions:

1. Absorption Economy
   a. For yield increase I and absorption coefficient C_A ranging from 0.7 to 1.5 and 10 per cent to 50 per cent, respectively, absorption economy varies from 2.54 to 89.00 and the average values of E_A for rice, soybean, sugar cane, and sweet potato are 18.75, 46.37, 10.52, and 50.54, respectively.
   b. Absorption economy E_A is directly proportional to C_A.
   c. Higher I increase K value ($k = \frac{IW_s}{(I + 1)R}$), which, in turn, improves E_A.
2. Distribution Economy
   a. Increasing carbon distribution cost decreases distribution economy E_D.
   b. For the design discussed in the study, E_D is 0.285.
3. Fertilization Economy
   a. Fertilization economy E_F is proportional to both E_A

and E_D.

b. Based on the E_D of the distribution system of this study, the breakeven point of E_F is reached when E_A reaches to 3.5, which is much lower than the values obtained for the crops. Therefore, E_F is likely to be very high and it is profitable to fertilize crops with carbon dioxide.

However, due to lack of a suitable device for the prevention of carbon dioxide diffusion loss for Type I crop, carbon dioxide fertilization can only be applied to Type II crop. Nevertheless, the air tight fence method is still practical for nursery bed, such as rice seedling bed, etc.

This study was originally intended to prove the possibility of utilizing carbon dioxide as a fertilizer and make decision whether any further field experiments are worthy of study, and also the type of experiments that should be attempted if the results should be on the positive side. Therefore, the conclusions resulting from this study will not lead to any practical method of applying carbon dioxide, but will shed only light on the problem of selecting future experiments, which will eventually lead to a concrete method of applying this fertilizer in an economical way. The recommendations for future experiments will be:

1. Conducting experiments concerning improvement of distribution system power consumption.
2. To apply the distribution design to actual crops in order to obtain actual crop increase I,

absorption coefficient C_A and other basic parameters, which will yield more precise information by plugging them into the derived equations. This check is definitely needed for the confirmation of the conclusions reached in this study and testing the validity of this evaluating method.

3. Measurement of carbon dioxide content in the air near the plant leaves to determine the degree of carbon dioxide exhaustion effect, which is suspected to be very low.
4. Conduct ventilation of crop experiments if the degree of exhaustion is found to be severe.
5. Determine the possibility of using high wind speed above the crops as a power source for distributing carbon dioxide and for crop ventilation purposes.

APPENDIX

Calculation of Maximum CO_2 Required by 1/10 Hectare Rice Field

Rice Normal Yield

Unhulled rice = 600 kg/0.1 ha.

straw = 615 kg/0.1 ha.

root = 249 kg/0.1 ha.

Total yield N = 600 + 615 + 249

= 1,464 kg/0.1 ha.

Carbon Needed

I = 1.5

Carbon for normal yield is also assumed to be supplied by CO_2 fertilizer.

R = 0.308 (for rice)

Carbon needed = N (I + 1) R

= 1,464 (1.5 + 1) 0.308

= 1,100 kg.

Fertilization Time

8.5 hours/day

Growth period of rice = 110 days

Total time = 8.5 x 110 x 60 = 56,100 minutes

Carbon to be Delivered Every Minute

$$= \frac{1{,}100}{56{,}100} = 0.0195 \text{ kg/min.}$$

Volume of CO_2 to be Delivered per Minute

$$= \frac{0.0195 \times 1{,}000 \text{ grams}}{12} \times 26.3$$

$= 42.7$ liters/min. or 1.5 cfm

Note: 1. Each 44 grams CO_2 contains 12 grams carbon and 44 grams CO_2 and will have a volume of 26.3 liters at 1 atmosphere and 80^oF.

2. 1 liter = 0.0353 cu. ft.

Maximum CO_2 Required

Assume absorption coefficient $C_A = 10\%$, then

Maximum CO_2 required per 1/10 ha. per minute

$$= \frac{1.5}{\frac{10}{100}} = 15 \text{ cfm}$$

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