Carbon Dioxide and Agricultural Yield: An Assemblage and Analysis of 430 Prior Observations[1]

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ABSTRACT

The probable effect of the increasing global atmospheric CO_2 concentration on agricultural yields was evaluated. More than 430 observations of the yield of 37 species grown with CO_2 enrichment were extracted from more than 70 reports published during the past 64 years. Most of the studies were performed in greenhouses or growth chambers. Open fields might respond less than greenhouses or growth chambers to increased CO_2 because nutrient levels in general world-wide agriculture are lower than those in the indoor studies, or open fields might respond more because light levels are generally higher outside. The data also were dominated by high value crops, but results should be applicable to the three-fourths of the world agriculture represented by the C_3 crops and possibly to the remaining C_4 crops as well. Keeping these limitations of the data in mind, the analysis showed that yields probably will increase by 33% (with a 99.9% confidence interval from 24 to 43%) with a doubling of atmospheric CO_2 concentration.

Additional index words: **CO_2, Enrichment, Increase, Supplement, Global, World, Productivity, Growth.**

THE CO_2 concentration of the atmosphere has been increasing for the past 50 years (Keeling et al., 1976), and may double by the year 2025 (Gribbin, 1981). Several theoretical models have predicted that the mean global air temperature will increase 3 to 4 °C with a doubling of the CO_2 concentration (Manabe and Wetherald, 1967; Ramanathan, 1981). Such a change could have serious effects on agriculture, although agriculture has demonstrated some resiliency for adaption to differing climates (Wittwer, 1980; Rosenberg, 1982; Kimball and Idso, 1982). However, more recent "earth experiments" indicate that the temperature rise will be less than 0.26°C for a doubling of CO_2 concentration (Idso, 1980, 1982a, 1982b), so the primary effect on agricultural production may only be that of the increased CO_2 concentration per se. The climate controversy is continuing and is beyond the scope of this paper, which will concentrate on the effects of elevated CO_2 concentrations on agricultural yield.

Numerous experiments have been performed to determine the effects of enriched CO_2 atmospheres on plants ever since 1804, when de Saussure (1804) first demonstrated that peas exposed to high CO_2 concentrations grew better than control plants in ambient air. These experiments have been reviewed occasionally (Wittwer and Robb, 1964; Wittwer, 1978, 1980; Allen, 1979; Kramer, 1981; Rosenberg, 1981), but a comprehensive review and analysis of their combined results is lacking. Thus, it is my purpose here to extract a definitive statement from these experiments about the quantitative effect on agricultural production that is likely to occur as a result of mankind's great CO_2 enrichment experiment, upon which we have already embarked.

METHODS

From more than 70 reports about effects of CO_2 enrichment on the economic yield of 24 agricultural crops and 14 other species, I have extracted more than 437 observations. These results are presented in detail in Kimball (1982), a report which is available by request from the author. It is a near comprehensive collection from the English literature, plus a few more from other languages, and is considerably more detailed than previous reviews. Only single stem determinate flower crops such as pot poinsettias (*Euphorbia pulcherrima* Willd. ex Kl.) that produce a single inflorescence were excluded. Appendices A, B, C, and D contain the details from that report for controlled experiments and simple ranges of data for the less controlled experiments. Appendix A contains the economic yield results from mature agricultural crops, while B, C, and D contain total dry weight or other results for immature agricultural (B) herbaceous (C) and woody (D) species.

Because the yield data came from a wide range of crops and conditions, it was necessary to standardize each experiment with respect to its own unenriched control in order to make meaningful comparisons. Therefore, I computed the relative increase or ratio of the CO_2-enriched plant yield to the control yield. These ratios were essentially lognormally distributed (Fig. 1). This can be readily understood by noting that if CO_2 enrichment were to double the yield, the ratio would be 2.0; whereas, if it were to halve the yield, the ratio would be 0.5. Thus, using the log transformation $X' = \log_{10}(X)$ linearized and normalized the distribution, i.e., $\log(0.5) = -0.30$, $\log(1.0) = 0.00$, $\log(2.0) = +0.30$. Consequently, if CO_2 enrichment had no significant effect on yield, one would expect the logarithms of the ratios to be normally distributed about a mean of zero. Taking the log of the ratio is also the same as taking the logs of the treated and of the controls separately and then subtracting the latter log from the former.

Although the actual distribution was somewhat skewed to the right (Fig. 1), the departure from normality was not great, so the means of the logarithms of the yield ratios and the 95 and 99.9% confidence intervals for the means were computed (Snedecor, 1956), and then antilogarithms were taken for presentation in the "Results."

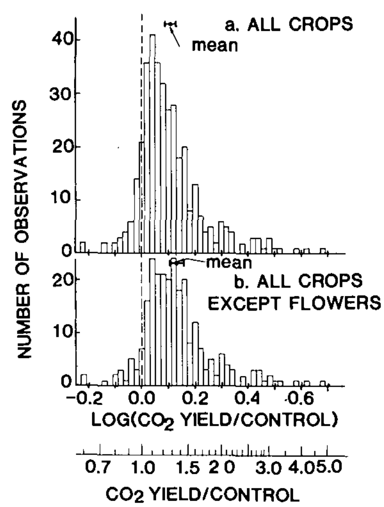

Fig. 1. Frequency distribution of the logarithms of the relative yield increases (ratios) of CO_2-enriched plants to their respective unenriched controls for: a. all mature agricultural crops and b. all mature agricultural weight crops excluding flowers. The points and associated brackets are the means and 99.9% confidence intervals for the means computed from the logarithms of the yield ratios.

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One "observation" in the analysis in this paper was taken as one yield ratio value. Some reported yields were actually means of observations from several replicates, but since only the mean was reported, only one value was available for use.

In addition to determining whether the increased CO_2 will have a qualitative effect, a quantitative prediction of how much yields will increase with a doubling or tripling of CO_2 concentration is needed. However, a number of obstacles arose when trying to extract such a quantitative prediction from the data. First, many workers did not report what concentrations were used. Second, even more used widely varying concentration, particularly those whose greenhouses had to be ventilated for temperature control on hot sunny days. Still other workers enriched their plants only for specific stages of growth. When only those experiments that had controlled and monitored CO_2 concentrations for their duration were considered, most of the experiments were eliminated. Further restricting to those with weight yields (excluding flowers) and concentrations of less than 1200 μL/L (an arbitrary cut-off point to focus on current rates of increase rather than on where a yield plateau occurs), only 38 mature agricultural crop experiments (Appendix A) and 43 immature plant experiments (Appendices B, C, and D) were left.[3] The average rate of yield ratio increase with CO_2 enrichment was determined for each of these 81 experiments. For those experiments with only two points, slopes were calculated from the single defined line, whereas least squares linear regression was used for those experiments with three or more points. The slopes appeared to be approximately lognormally distributed (Fig. 2), so the mean slope and 95 and 99.9% confidence intervals were computed using the transformation, $X' = \log(\text{slope} \times 10^3 + 1)$. The "1" was added in the transformation to avoid the mathematical impossibility of taking the logarithm of negative slopes.

The quality of the data base must also be considered. It is to be expected than any investigator finding large yield increases with CO_2 enrichment would be eager to report that result. However, it is also possible in such experiments that some mishap can befall the control plants, so that an apparent CO_2 benefit is only an artifact of a low control yield, due to something else. On the other hand, it is also possible that the CO_2 enrichment could have "saved" the treated plants from the misfortune of the control plants. Consequently, I compared the control yields within each crop, and those experiments with suspiciously low control yields were noted and excluded from further statistical calculations.

It is also possible that investigators finding no significant effects of CO_2 enrichment in their experiments may not bother reporting their results, or reviewers and editors might decline to publish them. Thus, we might expect a decrease in the number of reported observations near a CO_2/control yield ratio of 1.0. Yet, if the investigators found significantly reduced yields, we could expect that such results would be reported, and that the investigators would try to stop growers from investing in unprofitable CO_2. Finally, some negative effects of CO_2 enrichment might be blamed on toxic impurities and could go unreported; but I have assumed that most of the scientists doing work of this nature have been competent enough to take the precaution of checking the purity of their CO_2 sources. Thus, I feel that the reported CO_2 enrichment experiments represent a true population, except for some possible underreporting close to a ratio of 1.0 and for some bias at really high ratios due to possible low control yields.

RESULTS

As one scans the Appendices, it is apparent that CO_2 enrichment has had an overwhelmingly positive effect on yield. Of 437 separate observations (Kimball, 1982), only 39 yielded less than their respective controls. Of this group, 20 were flower crops whose yields were measured by number of flowers rather than by weight. Frequency distributions of logarithms of the relative yield increases (ratios) are plotted in Fig. 1a for all of the mature agricultural crops and in Fig. 1b excluding flowers. Results of the few CO_2 depletion experiments were not included. The mode ratio is about 1.1, considering all observations (Fig. 1a), or about 1.2, considering only the weight yield ratios and smoothing the curve (Fig. 1b). Although the distributions are somewhat skewed to the right, the departure from normality is not great. The large number of data points made the confidence intervals relatively short. Considering all the mature agricultural crops, the average relative yield increase was 1.28 or 1.36 excluding flowers. Means for each crop and their respective 95 and 99.9% confidence intervals are presented in Table 1. Crops listed there are also grouped according to the plant organs marketed; and overall means and confidence intervals for each group are also presented. Effects of CO_2 concentration on some of the individual crops are difficult to predict, due to a paucity of data. The cotton results, for instance, indicate that a doubling of CO_2 concentration could more than double yields, but unfortunately, there are only two data points. Effects of CO_2 enrichment on flower yields were generally smaller than effects on other crops, but this result is not surprising because the flower yields were the number of blooms per plant. Mean yield ratios of the other crops categories with more than three observations were 1.23, 1.32, 1.42, 1.54, and 1.52 for fruit, C_3 grain, leaf, legume seed, and root crops, respectively (Table 1). The fruit yield ratio (dominated by tomato (*Lycopersicon esculentum* Mill.) with a mean yield ratio of 1.20) is somewhat lower than those of the other weight crops. This may partly be due to the fact that many of the tomato experiments were done in ventilated greenhouses and not enriched with CO_2 for a portion of the time, whereas relatively more of the experiments with other crops were done with growth chambers that were continuously enriched.

Also included in Table 1 are the mean relative yield increases or ratios with confidence intervals for 79 ob-

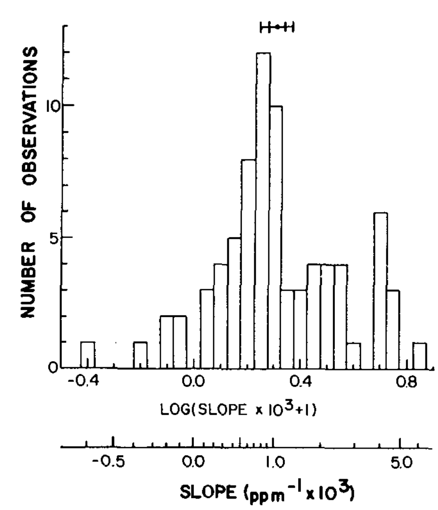

Fig. 2. Frequency distribution of the transformed slopes (change in relative yield increase per 1000 μL/L change in CO_2 concentration). The slopes were transformed using $X' = \log(\text{slope} \times 10^3 + 1)$. The point and associated brackets are the mean and the 95 and 99.9% confidence intervals for the mean, respectively.

[3] The non-SI unit ppm has been retained because CO_2 concentration was reported in that unit.

servations from experiments that were terminated before the plants matured. Without exception these experiments were performed using controlled CO_2 enrichment for their duration, and the resultant mean yield ratio of 1.60 is significantly higher than the mean yield ratios of 1.28 or 1.36 for the mature plants. When these immature plant results are pooled with the mature, the overall resultant mean relative yield increase with CO_2 enrichment is 1.33 with a 99.9% confidence interval from 1.27 to 1.40.

The frequency distribution of all the transformed slopes of the yield ratio lines is plotted in Fig. 2. This distribution is more jagged than that in Fig. 1, but the number of observations is much smaller. The mode

Table 1. Mean relative yield increases (ratios) of CO_2-enriched to control crops and associated confidence intervals. The means and confidence limits were computed from logarithms of ratios and then transformed by taking antilogarithms.

Crop	No. of observations	Lower limit −99.9%	Lower limit −95%	Mean	Upper limit 95%	Upper limit 99.9%
Mature agricultural crops (marketable yield)						
Fiber crops:						
cotton	2	--	--	2.59	--	--
Flower crops: (no. of blooms)						
carnation	25	1.01	1.05	1.09	1.13	1.17
chrysanthemum	58	1.02	1.03	1.06	1.09	1.10
cyclamen	3	--	0.48	1.35	3.78	2550
nasturtium	3	--	0.61	1.86	5.69	6917
rose	20	1.03	1.11	1.22	1.33	1.44
snapdragon	1	--	--	1.03	--	--
all flower crops	110	1.06	1.08	1.12	1.16	1.18
Fruit crops:						
cucumber	12	1.14	1.22	1.30	1.38	1.47
eggplant	2	--	--	2.54	--	--
strawberry	10	0.74	0.96	1.22	1.54	2.00
sweet pepper	1	--	--	1.20	--	--
tomato	72	1.12	1.15	1.20	1.24	1.28
all fruit crops	97	1.15	1.18	1.23	1.28	1.32
Grain crops (C3):						
barley	3	0.09	0.88	1.25	1.77	16.2
rice	11	1.01	1.13	1.25	1.39	1.56
wheat	20	1.11	1.22	1.37	1.53	1.69
all C3 grain crops	34	1.16	1.23	1.32	1.42	1.50
Grain crops (C4):						
sorghum	2	--	--	2.98	--	--
Leaf crops:						
endive	1	--	--	1.15	--	--
lettuce	54	1.19	1.26	1.35	1.45	1.53
Swiss chard	17	1.05	1.30	1.67	2.13	2.66
all leaf crops	72	1.24	1.31	1.42	1.53	1.62
Legume seed crops:						
beans	5	0.62	1.29	1.82	2.59	5.38
peas	7	0.79	1.32	1.89	2.70	4.51
soybean	12	1.01	1.13	1.27	1.43	1.60
all legume crops	24	1.20	1.34	1.54	1.77	1.99
Root and tuber crops:						
potato	12	0.95	1.25	1.64	2.14	2.81
radish	5	0.33	0.83	1.28	1.96	4.86
all root/tuber crops	17	1.02	1.23	1.52	1.88	2.26
All mature agric. crops	358	1.22	1.24	1.28	1.32	1.35
All except flowers	247	1.28	1.31	1.36	1.42	1.45
Immature crops (total plant weight or height)						
Agricultural crops	56	1.39	1.49	1.64	1.81	1.94
Non-agric., herbaceous	12	1.06	1.22	1.38	1.58	1.80
Woody plants	11	1.23	1.42	1.62	1.84	2.11
All immature	79	1.41	1.48	1.60	1.72	1.81
All mature plus immature	437	1.27	1.30	1.33	1.37	1.40

slope is about 0.00078/(μL/L) and the mean is about 0.00100/(μL/L). The results of the statistical analyses of the slopes are presented in Table 2 separately for the mature and immature agricultural crops and for the immature non-agricultural and woody classes. The mean slope is 0.00096/(μL/L), with a 95% confidence interval from 0.00062 to 0.00136/(μL/L) for the mature agricultural crops. The mean slopes for the immature crops are not significantly different from that for the mature crops. Pooling the data, the overall mean slope is 0.001000 with a 95% confidence interval from 0.00085 to 0.00117.

Using the overall mean slope in Table 2 and present-day CO_2 concentration of 330 μL/L, the relative yield increases at future concentrations of 660 μL/L (doubling) and 1000 μL/L (tripling) were predicted. At a CO_2 concentration of 660 μL/L, mean yields are predicted to be 1.33 times greater than now with a 95% confidence interval from 1.57 to 1.78. Thus, these existing data indicate that a doubling of the earth's CO_2 concentration will probably increase agricultural yield by about 33%, with a 95% confidence range from 28 to 39%.

DISCUSSION

The question to now be addressed is how representative of worldwide agriculture is this 33% yield increase derived from prior CO_2 enrichment experiments? The final overall response will be an average weighted for the area planted to each crop and for the responsiveness of each crop within the wide range of environmental conditions characteristic of open-field agriculture. Most of the prior CO_2 enrichment experiments were done on high value horticultural crops (Table 1), rather than on major world food crops—wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), corn (*Zea mays* L.), and barley (*Hordeum vulgare* L.)—and they were performed in greenhouses or growth chambers in which the temperature was controlled to be more ideal for plant growth.

First, the overall response of field grown crops to increased CO_2 concentration ought to be as large or larger than greenhouse-grown crops. Considering spe-

Table 2. Means and confidence intervals for the change in relative yield increase per 1000 μL/L change in CO_2 concentration (slopes) for those experiments having controlled CO_2 concentrations. Also the subsequent predicted relative mean yield increase and confidence intervals for a 660 μL/L CO_2 concentration (atmospheric doubling) and for a 1000 μL/L CO_2 concentration (atmospheric tripling) based on the overall mean slope. The means and confidence intervals were computed using the transformation $X' = \log(\text{slope} \times 10^3 + 1)$.

Item	No. of observations	Lower limit −99.9%	Lower limit −95%	Mean	Upper limit +95%	Upper limit +99.9%
Slopes [change in relative yield increase/change in CO_2 concentration (ppm)] × 10^3						
Mature agric. crops	38	0.41	0.62	0.96	1.36	1.73
Immature agric. crops	31	0.61	0.87	1.26	1.72	2.16
Immature non-agric. crops	6	−0.39	0.04	0.42	0.97	2.35
Immature woody	6	−0.14	0.34	0.75	1.29	2.58
All mature plus immature	81	0.74	0.85	1.00	1.17	1.30
Yield increase at 660 μL/L CO_2		1.24	1.28	1.33	1.39	1.43
Yield increase at 1000 μL/L CO_2		1.50	1.57	1.67	1.78	1.87

cific differences between greenhouses (or growth chambers) and open fields, the environments in greenhouses generally have more (1) ideal temperature, (2) optimum humidity and soil moisture, (3) adequate nutrients, and (4) reduced solar radiation. With respect to temperature, the data probably adequately represent the field because photosynthesis responses to changing CO_2 concentration are not markedly different at different temperatures over a range at which the crops are normally grown (Gaastra, 1959; Enoch and Hurd, 1977).

The more ideal moisture conditions in greenhouses also do not invalidate the data because the two CO_2 enrichment studies which included moisture stress as a variable showed that water-stressed wheat responded to CO_2 about as much or more than well-watered wheat (Gifford, 1979a, 1979b; Sionit et al., 1980). Also, short-term experiments have shown that transpiration is reduced as CO_2 is increased (Pallas, 1965; Carlson and Bazzaz, 1980; Rosenberg, 1982; Kimball and Idso, 1982), so even if the greenhouse data do not represent the field with respect to water, any bias is likely to be in a conservative direction, i.e., that moisture-limited field crops are likely to respond more to increased CO_2 than the well-watered greenhouse crops.

With respect to nutrients, the data may be somewhat biased because some experiments (Sionit et al., 1981b; Wong, 1979) have shown reduced response to CO_2 enrichment at low nutrient levels. Thus, crops grown without added fertilizer on infertile soils probably will benefit relatively less from increased CO_2, which also means that less developed countries may benefit less than developed countries.

With respect to solar radiation, the data may also be biased, but in the direction opposite of that for nutrients. Photosynthesis and yield increase more with CO_2 enrichment at the higher light intensities characteristic of field conditions than at the lower intensities typical of greenhouses, particularly in winter (Gaastra, 1979; Enoch and Hurd, 1977; Kimball and Mitchell, 1979). Also, under the highest light intensities many of the greenhouses were not enriched, because ventilation was used for temperature control, in contrast to future fields which will have higher CO_2 concentrations continuously. Thus, there is probably a large conservative bias in the greenhouse data.

Second, the plant species used for the prior CO_2 enrichment experiemnts can reasonably be expected to be representative of most of the world's agriculture. The consensus of opinion among members of the "Whole Plant Growth and Development" panel at the recent conference on "Rising Atmospheric Carbon Dioxide and Plant Productivity" was that the primary effect of increased CO_2 will be that rates of photosynthesis will increase and produce more carbohydrates for plant growth (Baker et al., 1982). About three-fourths of the world grain production is from C_3 species—wheat, rice, and barley (USDA, 1981)—which use the same photosynthetic machinery as the main greenhouse crops. The data in Table 1 indicate that C_3 grains respond similarly to the other crops. On the other hand, C_4 crops—maize (*Zea mays* L.), sorgum (*Sorghum bicolor* (L.) Moench.), sugarcane (*Saccharum officinarum* L.)—and the CAM crop—pineapple [*Ananas comosus* (L.) Merr.]—are under-represented by the data. Furthermore, the few existing C_4 data conflict. The seven corn and itchgrass (*Rottboellia exaltata* L.) slopes from Wong (1979), Patterson and Flint (1980), and Carlson and Bazzaz (1980), indicate that the growth response of C_4 plants to increased CO_2 is likely to be about one-fourth that of C_3 crops. On the other hand, Rogers et al. (1980) recently found using open-top field chambers that corn yield increased with CO_2 concentration at a rate double the average for all crops. A similar rate was obtained by Riley and Hodges (1969) with sorghum. Thus, the prior results ought to be representative of the largest portion of agriculture, consisting of C_3 plants and possibly also C_4 plants.

CONCLUSION

Plants are complex organisms, and undoubtedly there will be species differences and specific environmental differences affecting the amount by which the increased carbohydrate supply from increased CO_2 is transformed into marketable yield. Certainly more data are needed for the major crops, particularly C_4 and CAM crops, from field and controlled environment experiments with normal as well as water- and nutrient-stressed plants. Considering the variability inherent in such work (Table 1), however, the large body of prior experimental data is sufficiently representative to provide a more reliable prediction of future CO_2 effects than can be obtained from the limited number of such experiments that are in progress or planned for the next several years. Thus, it appears from the analysis of the prior data that agricultural yields will increase overall by about 33% with a doubling of the earth's CO_2 concentration.

APPENDIX A

Results of individual CO_2 enrichment experiments with mature agricultural crop plants. The details are presented only for those experiments which maintained controlled CO_2 concentrations of 1200 μL/L or less for the entire (or nearly so) life span of the crop. The yield ratio range and the number of observations are presented for other experiments which did not meet these criteria. The slopes are the rate of change of yield ratio with CO_2 concentration. More information is presented in Kimball (1982), which is available by request from the author.

	CO_2 conc. (μL/L)	Yield	Yield ratios	Comment (No. Obs.)	Investigators
barley (*Hordeum vulgare*), (g grain per m²):					
1.	305	329			Gifford et al. (1973)
	706	471	1.43		
	Slope: 0.00107/(μL/L)				
2.			1.08–1.26	(2)	Gifford et al. (1973)
beans (*Phaseolus vulgaris*), (g fresh weight of beans per plant):					
1.			1.12–2.16	(5)	Cummings and Jones (1918)
carnation (*Dianthus caryophyllus* L.), (flowers per m²):					
1.	normal	6.1		the yield units	Holley and Altstadt (1966)
	525	7.5	1.23	are per week for	
	525	6.2	1.02	an unreported	
	525	6.6	1.08	number of weeks	
	525	7.0	1.15		
2.			1.08	(1)	Goldsberry (1966)
3.	200	381	(0.78)	depletion	Goldsberry (1961)
	350	494			
	350	482		flower per chamber	
	550	521	1.07		
4.			1.14	(1)	Goldsberry (1963)
5.			1.08–1.33	(3)	Holley et al. (1964)
6.			1.00–1.03	(2)	Holley (1967)

(continued)

Appendix A Continued.

	CO_2 conc. (μL/L)	Yield	Yield ratios	Comment (No. Obs.)	Investigators
7.			1.15	(1)	Holley et al. (1962)
8.			0.96–1.20	(8)	McKeag (1965)
9.			0.89–1.12	(4)	Koths and Adzima (1967)
chrysanthemum (*Chrysanthemum morifolium*), (flowers per m²):					
1.			0.86–1.20	(21)	Nelson and Larson (1969)
2.	300	52		"Yellow Delaware"	Walla and Kristoffersen (1974)
	1000	55	1.04	@ 15 C, 3500 lux	
3.	300	57		"Yellow Delaware"	Walla and Kristoffersen (1974)
	1000	68	1.20	@ 15 C, 7000 lux	
4.	300	69		"Yellow Delaware"	Walla and Kristoffersen (1974
	1000	72	1.04	@ 15 C, 14000 lux	
5.	300	50		"Yellow Delaware"	Walla and Kristoffersen (1974)
	1000	61	1.22	@ 21 C, 3500 lux	
6.	300	65		"Yellow Delaware"	Walla and Kristoffersen (1974)
	1000	64	0.98	@ 21 C, 700 lux	
7.	300	83		"Yellow Delaware"	Walla and Kristoffersen (1974)
	1000	80	0.96	@ 21 C, 14000 lux	
8.	300	65		"White Pot"	Walla and Kristoffersen (1974)
	1000	66	1.02	@ 15 C, 3500 lux	
9.	300	67		"White Pot"	Walla and Kristoffersen (1974)
	1000	76	1.13	@ 15 C, 7000 lux	
10.	300	94		"White Pot"	Walla and Kristoffersen (1974)
	1000	102	1.08	@ 15 C, 14000 lux	
11.	300	69		"White Pot"	Walla and Kristoffersen (1974)
	1000	80	1.16	@ 21 C, 3500 lux	
12.	300	80		"White Pot"	Walla and Kristoffersen (1974)
	1000	91	1.15	@ 21 C, 7000 lux	
13.	300	118		"White Pot"	Walla and Kristoffersen (1974)
	1000	115	0.97	@ 21 C, 14000 lux	
14.			0.95–1.34	(24)	Walla and Kristoffersen (1974)
cotton (*Gossypium hirsutum*), (g lint per plant):					
1.	330	61			Mauney et al. (1978)
	630	170	2.79		
	Slope: 0.00597/(μL/L)				
2.	350	20		Nine plants in 1 m² area with border in greenhouse harvested @ 175 days	Mauney et al. (personal communication)
	650	49	2.41		
	Slope: 0.00470/(μL/L)				
cucumber (*Cucumis sativus*), (kg fresh fruits/m²):					
1.			1.43	(1)	Enoch et al. (1970)
2.			1.18–1.26	(3)	Enoch et al. (1976)
3.			1.16	(1)	Owen et al. (1926)
4.			1.14–1.27	(3)	Meensaln et al. (1976)
5.	normal	5.28		"Delena"	Willits and Peet (1981)
	1000	5.98	1.32	kg marketable fruit per plant	
	Slope: 0.00048/(μL/L)				
6.	normal	5.19		"Sandra"	Willits and Peet (1981)
	1000	7.38	1.42	kg fruit/plant	
	Slope: 0.00063/(μL/L)				
7.	normal	4.20		"Vetomil"	Willits and Peet (1981)
	1000	6.75	1.61	kg fruit/plant	
	Slope: 0.00091/(μL/L)				
8.	normal	4.65		"Silvia"	Willits and Peet (1981)
	1000	6.33	1.36	kg fruit/plant	
	Slope: 0.00054/(μL/L)				
cyclamen (*Cyclamen* sp.), (no. flowers per plant):					
1.			0.97–2.15	(3)	Cummings and Jones (1918)
eggplant (*Solanum melongena*), (g fresh weight fruit per plant):					
1.	200	862	(1.17)	depletion	Imazu et al. (1967b)
	300	735			
	900	1536	2.09		
	Slope: 0.00149/(μL/L)				
2.			3.09	(1)	Imazu et al. (1967b)
endive (*Cichorium endivia*), (g fresh weight leaves per plant):					
1.			1.15	(1)	Cummings and Jones (1918)
lettuce (*Lactuca sativa*), (grams of fresh head weight per plant):					
1.	400	73			Pettibone et al. (1970)
	800	143	1.96		
	1200	189	2.59		
	Slope: 0.00199/(μL/L)				
2.			2.84	(1)	Pettibone et al. (1970)

(continued)

Appendix A Continued

	CO_2 conc. (μL/L)	Yield	Yield ratios	Comment (No. Obs.)	Investigators
3.			1.16–2.00	(14)	Wittwer and Robb (1964)
4.			1.43	(1)	Enoch et al. (1970)
5.			0.74–1.68	(25)	Cummings and Jones (1918)
6.	300	435			Imazu et al. (1967c)
	900	811	1.87		
	Slope: 0.00145/(μL/L)				
7.			2.04–2.41	(2)	Imazu et al. (1967c)
8.			1.22–1.35	(8)	Maxon Smith (1977)
nasturtium (*Tropaeolum majus*), (no. flowers per plant):					
1.			1.22–2.99	(3)	Cummings and Jones (1918)
peas (*Pisum sativum*), (g fresh weight per plant):					
1.			1.27–3.08	(7)	Cummings and Jones (1918)
potatoes (*Solanum tuberosum*), (g fresh weight tubers per plant):					
1.			1.43–1.75	(2)	Collins (1976)
2.			1.07–4.25	(10)	Cummings and Jones (1918)
radish (*Raphanus sativus*), (g fresh weight root per plant):					
1.			0.92–2.19	(5)	Cummings and Jones (1918)
rice (*Oryza sativa* L.), (g grain per m²)					
1.	300	810		"Calusa"	Riley and Hodges (1969)
	1000	960	1.19		
	Slope: 0.000271/(μL/L)				
2.	300	1000		"IR-8"	Riley and Hodges (1969)
	1000	1400	1.4		
	Slope: 0.000444/(μL/L)				
3.			1.4–1.8	(2)	Riley and Hodges (1969)
4.			1.21–1.29	(3)	Cock and Yoshida (1973)
5.			1.00–1.30	(5)	Yoshida (1973)
rose (*Rosa* spp.), (blooms per bush):					
1.			1.08–1.27	(3)	Goldsberry and Holley (1962)
2.			1.11–1.36	(3)	Hand and Cockshull (1975)
3.			1.60	(1)	Lindstrom (1965)
4.			0.73–2.05	(5)	Loginov (1976)
5.			1.08–1.34	(8)	Mattson and Widmer (1971)
snapdragon (*Antirrhinum majus*), (no. flowers per plant):					
1.			1.03	(1)	Koths (1963)
sorghum (*Sorghum bicolor*), (g grain/m²):					
1.	300	220			Riley and Hodges (1969)
	1000	390	2.68		
	Slope: 0.00240/(μL/L)				
2.			3.32	(1)	Riley and Hodges (1969)
soybean (*Glycine max*), (g grain per m²):					
1.	300	400			Riley and Hodges (1969)
	1200	560	1.40		
	Slope: 0.00444/(μL/L)				
2.			1.28	(1)	Riley and Hodges (1969)
3.			1.41–1.57	(2)	Copper and Brun (1967)
4.	<425	110		(g grain per plant)	Hardman and Brun (1971)
	1200	151	1.37	continuous	
	Slope: 0.000425/(μL/L)				
5.			0.95–1.25	(3)	Hardman and Brun (1971)
6.			1.05–1.22	(3)	Shivashankar et al. (1976)
7.			1.78	(1)	Havelka and Hardy (1976)
strawberry (*Fragaria* spp.), (g fresh weight of berries per plant):					
1.			1.31–1.51	(3)	Enoch et al. (1976)
2.			0.60–1.86	(7)	Cummings and Jones (1918)

(continued)

Appendix A Continued.

	CO_2 conc. (μL/L)	Yield	Yield ratios	Comment (No. Obs.)	Investigators
sweet pepper (*Capsicum annuum*), (kg fresh fruit per plant):					
1.			1.20	(1)	Enoch et al. (1970)
Swiss chard (*Beta vulgarus*, var. *cicla*), (g fresh weight per plant):					
1.	300	16.2		summer	Imazu et al. (1967a)
	600	15.0	0.93		
	900	35.6	2.20		
	Slope: 0.00200/(μL/L)				
2.	300	2.6		winter	Imazu et al. (1967a)
	900	2.8	1.08		
	Slope: 0.000133/(μL/L)				
3.			1.69–4.74	(4)	Imazu et al. (1967a)
4.	300	95		g dry weight per m²	Yabuki et al. (1967)
	700	120	1.26	@ 50 plants/m²	
	Slope: 0.000650/(μL/L)				
5.	300	150		g dry weight per m²	Yabuki et al. (1967)
	700	205	1.37	@ 120 plants/m²	
	Slope: 0.000925/(μL/L)				
6.	300	270		g dry weight per m²	Yabuki et al. (1967)
	700	230	0.85	@ 275 plants/m²	
	Slope: −0.000375/(μL/L)				
7.			1.06–3.23	(6)	Yabuki et al. (1967)
8.			1.65	(1)	Cummings and Jones (1918)
tomato (*Lycopersicon esculentum*), (kg fresh fruit plant @ about 2.7 plants/m²):					
1.			1.25–1.71	(9)	Wittwer and Robb (1964)
2.			1.30–1.31	(2)	Calvert (1972)
3.			1.05–1.24	(16)	Kretchman and Howlett (1970)
4.			1.02–1.10	(6)	Bauerle and Kretchman (1973)
5.			1.26–1.39	(3)	Calvert and Slack (1975)
6.			1.10–1.18	(2)	Hand and Postlethwaite (1971)
7.	350	1.9			Madsen (1974)
	650	2.2	1.16	1 month of picking	
	1000	2.8	1.47		
	Slope: 0.000728/(μL/L)				
8.			0.59–1.37	(3)	Madsen (1974)
9.			1.21–1.49	(2)	Morgan (1971)
10.			1.25	(1)	Owen et al. (1926)
11.			1.14–1.46	(3)	Cooper (1967)
12.			1.02–1.19	(5)	Small and White (1930)
13.			1.28–1.32	(2)	Meensaln et al. (1976)
14.			1.42	(1)	Hicklenton and Jolliffe (1978)
15.			1.09–1.28	(4)	Libik and Wojtaszek (1977)
16.	normal	8.6		ventilated	Kimball and Mitchell (1979)
	650	10.1	1.17	unventilated	
	1000	12.6	1.48	unventilated	
	Slope: 0.00731/(μL/L)			("Tropic", spring 1977)	
17.	normal	9.1		ventilated	Kimball and Mitchell (1979)
	1000	13.7	1.50	unventilated	
	Slope: 0.000758/(μL/L)			(Tropic, winter 77-78)	
18.	normal	6.7	0.84	ventilated	Kimball and Mitchell (previously unpublished)
	1000	5.6	0.84	unventilated	
	Slope: −0.000197/(μL/L)			("N-65", fall 1978)	
19.	normal	12.2		ventilated	Kimball and Mitchell (previously unpublished)
	1000	15.2	1.25	unventilated	
	Slope: 0.000379/(μL/L)			("Tropic", spring 1979, total kg fruit per plant)	
20.			0.84–1.48	(5)	Kimball and Mitchell (1979 and previously unpublished)
21.			1.15	(1)	Willits and Peet (1981)
wheat (*Triticum aestivum*), (g grain per m²):					
1.			1.03–1.38	(6)	Krenzer and Moss (1975)
2.	150	540	(0.56)	depletion	Gifford (1977)
	300	970			
	500	1400	1.44		
	Slope: 0.00250/(μL/L)				

(continued)

Appendix A Continued.

	CO_2 conc. (μL/L)	Yield	Yield ratios	Comment (No. Obs.)	Investigators
3.	340	200		"Gabo"	Gifford (1979b)
	590	400	2.00	water limited	
	Slope: 0.00400/(μL/L)				
4.	340	720		"Gabo", water	Gifford (1979b)
	590	1100	1.53	not limited	
	Slope: 0.00212/(μL/L)				
5.	340	200		"WW15"	Gifford (1979b)
	590	400	2.00	water limited	
	Slope: 0.00400/(μL/L)				
6.	340	720		"WW15", water	Gifford (1979b)
	590	950	1.32	not limited	
	Slope: 0.00128/(μL/L)				
7.	350	23.5		no water stress	Sionit et al. (1980)
	1000	38.1	1.62	(g grain per plant)	
	Slope: 0.000954/(μL/L)				
8.	350	13.6		one water stress cycle	Sionit et al. (1980)
	1000	25.7	1.89	(g grain per plant)	
	Slope: 0.00137/(μL/L)				
9.	350	16.5		two water stress cycles	Sionit et al. (1980)
	1000	23.4	1.42	(g grain per plant)	
	Slope: 0.000646/(μL/L)				
10.	350	23.5		(g grain per plant)	Sionit et al. (1981a)
	675	37.5	1.60		
	1000	38.1	1.62		
	Slope: 0.00095/(μL/L)				
11.	350	13.8		1/16 Hoaglund's	Sionit et al. (1981b)
	675	11.0	0.80	(g grain/plant)	
	Slope: −0.00061/(μL/L)				
12.	350	21.6		1/8 Hoaglund's	Sionit et al. (1981b)
	675	23.0	1.06	(g grain/plant)	
	Slope: 0.00018/(μL/L)				
13.	350	28.2		1/2 Hoaglund's	Sionit et al. (1981b)
	675	37.5	1.33	(g grain/plant)	
	Slope: 0.00102/(μL/L)				
14.	350	22.0		1/1 Hoaglund's	Sionit et al. (1981b)
	675	34.0	1.55	(g grain/plant)	
	Slope: 0.00169/(μL/L)				

APPENDIX B

Results of individual CO_2 enrichment experiments with immature agricultural crop plants. The details are presented only for those experiments which maintained controlled CO_2 concentrations of 1200 μL/L or less for the duration of the experiment. The yield ratio range and the number of observations are presented for other experiments which did not meet these criteria. The slopes are the rate of change of yield ratio with CO_2 concentration. The yield units are grams dry weight per plant unless otherwise noted.

	CO_2 conc. (μL/L)	Yield	Yield ratios	Comment (No. Obs.)	Investigators
barley (*Hordeum vulgare*), (g dry wt/pot)					
1.	300	11.7		@ 39 days, 25 W/m²	Ford and Thorne (1967)
	1000	17.7	1.51	visible light	
	Slope: 0.00073/(μL/L)				
2.	300	20.4		@ 39 days, 60 W/m²	Ford and Thorne (1967)
	1000	28.1	1.38	visible light	
	Slope: 0.00054/(μL/L)				
3.			1.77–1.78	(2)	Ford and Thorne (1967)
beans (*Phaseolus vulgaris*)					
1.	300	1.41		@ 21 days	Tognoni et al. (1967)
	1000	2.40	1.70		
	Slope: 0.00100/(μL/L)				
corn (*Zea mays*) (C4 plant)					
1.	300	--		@ 35 days	Carlson and Bazzaz (1980)
	600	--	1.24		
	1000	--	0.93		
	Slope: −0.00014/(μL/L)				

(continued)

Appendix B Continued.

	CO_2 conc. (μL/L)	Yield	Yield ratios	Comment (No. Obs.)	Investigators
2.	350	91.29		@ 45 days	Patterson and Flint (1980)
	600	89.49	0.98		
	1000	80.08	0.88		
	Slope: −0.00019/(μL/L)				
3.	330	31	1.13	@ 30 days	Wong (1979)
	640	35	1.13	24 m*M* nitrate	
	Slope: 0.00042/(μL/L)				
4.	330	25		@ 30 days	Wong (1979)
	640	30	1.20	12 m*M* nitrate	
	Slope: 0.00065/(μL/L)				
5.	330	18		@ 30 days	Wong (1979)
	640	22	1.22	4 m*M* nitrate	
	Slope: 0.00071/(μL/L)				
6.	330	10		@ 30 days	Wong (1979)
	640	11	1.10	0.6 m*M* nitrate	
	Slope: 0.00032/(μL/L)				
cotton (*Gossypium hirsutum*)					
1.	330	21		@ 40 days	Wong (1979)
	640	48	2.29	24 m*M* nitrate	
	Slope: 0.00416/(μL/L)				
2.	330	16		@ 40 days	Wong (1979)
	640	39	2.43	12 m*M* nitrate	
	Slope: 0.00461/(μL/L)				
3.	330	12		@ 40 days	Wong (1979)
	640	27	2.25	4 m*M* nitrate	
	Slope: 0.00403/(μL/L)				
4.	330	9		@ 40 days	Wong (1979)
	640	17	1.89	0.6 m*M* nitrate	
cucumber (*Cucumis sativas*)					
1.			1.38	(1)	Krizek et al. (1974)
2.	300	29		fresh weight	Aoki and Yabuki (1977)
	1200	48	1.65	@ 24 days	
	Slope: 0.0072/(μL/L)				
3.			1.07–1.52	(2)	Aoki and Yabuki (1977)
4.	350	2		@ 21 days	Hopen and Ries (1962)
	450	3.5	1.75		
	500	3.0	1.50		
	Slope: 0.00393/(μL/L)				
5.			3.75	(1)	Hopen and Ries (1962)
lettuce (*Lactuca sativa*)					
1.			0.88	(1)	Krizek et al. (1974)
okra (*Hibiscus esculentus*)					
1.	400	25		g. fresh wt. per	Pettibone et al. (1970)
	800	39	1.56	plant @ 48 days	
	1200	80	3.20		
	Slope: 0.00275/(μL/L)				
2.			4.12	(1)	Pettibone et al. (1970)
peas (*Pisum sativum*)					
1.	320	0.37		@ 4 weeks	Phillips et al. (1976)
	1200	0.62	1.68		
	Slope: 0.00077/(μL/L)				
pepper (*Capsicum annuum*)					
1.	amb.	0.17		@ 28 days	Willits and Peets (1981)
	1000	0.41	2.41		
	Slope: 0.00210/(μL/L)				
radish (*Raphanus sativus*)					
1.	300	1.11		@ 23 days	Pettibone et al. (1970)
	900	2.26	2.04		
	Slope: 0.00173/(μL/L)				
2.			1.62	(1)	Pettibone et al. (1970)
3.	400	5.09		fresh weight	Knecht (1975)
	1200	15.37	3.20	@ 19 days	
	Slope: 0.00253/(μL/L)				
soybean (*Glycine max*)					
1.	300				Carlson and Bazzaz (1980)
	600		1.58	@ 35 days	
	1000		1.75		
	Slope: 0.00104/(μL/L)				
2.	350	50.55		@ 45 days	Patterson and Flint (1980)
	600	62.19	1.23		
	1000	87.09	1.72		
	Slope: 0.00112/(μL/L)				

(continued)

Appendix B Continued.

	CO_2 conc. (μL/L)	Yield	Yield ratios	Comment (No. Obs.)	Investigators
sugar beet (*Beta saccharifera*)					
1.	300	10.3		@ 57 days	Ford and Thorne (1967)
	1000	16.6	1.61	25 W/m² visible light	
	Slope: 0.0087/(μL/L)				
2.	300	21.5		@ 57 days	Ford and Thorne (1967)
	1000	32.6		58 W/m² visible light	
3.			1.72–1.80	(2)	Ford and Thorne (1967)
sunflower (*Helianthus annuus*)					
1.	300			@ 35 days	Carlson and Bazzaz (1980)
	600		1.20		
	1000		1.38		
	Slope: 0.00054/(μL/L)				
tomato (*Lycopersicon esculentum*)					
1.	300	0.77		@ 21 days	Tognoni et al. (1967)
	1000	1.57	2.04		
	Slope: 0.00149/(μL/L)				
2.	300	1.20		@ 45 days	Swalls and O'Leary (1976)
	900	1.56	1.30		
	Slope: 0.00050/(μL/L)				
3.			1.55	(1)	Swalls and O'Leary (1976)
4.			1.44	(1)	Krizek et al. (1974)
5.	amb.	0.35		@ 28 days	Willits and Peet (1981)
	1000	0.59	1.69	'Williamette cherry'	
	Slope: 0.00103/(μL/L)				
6.	amb.	0.38		@ 28 days	Willits and Peet (1981)
	1000	0.85	2.24	'Homestead #24'	
	Slope: 0.00185/(μL/L)				
7.	300	0.25		@ 23 days	Pettibone et al. (1970)
	900	0.85	3.44		
	Slope: 0.00407/(μL/L)				
8.			2.80	(1)	Pettibone et al. (1970)
wheat (*Triticum aestivum*)					
1.	200	1.39	0.79	(depletion)	Neals and Nicholls (1978)
	300	1.75		@ 24 days	
	400	1.88	1.07		
	600	1.92	1.10		
	800	1.86	1.06		
	Slope: 0.00037/(μL/L)				
2.	300	3.7		g. leaves/plant	Riley and Hodges (1969)
	1200	7.4	2.00	@ 30 days	
	Slope: 0.00111/(μL/L)				
3.			2.38	(1)	Riley and Hodges (1969)

APPENDIX C

Results of individual CO_2 enrichment experiments with non-agricultural herbaceous species. The slopes are the rate of change of yield ratio with CO_2 concentration. The yield units are grams dry weight per plant.

	CO_2 conc. (μL/L)	Yield	Yield ratios	Comment (No. Obs.)	Investigators
itchgrass (*Rottboellia exaltata*) (C4 plant)					
1.	350	39.24		@ 45 days	Patterson and Flint (1980)
	600	47.47	1.21		
	1000	38.62	0.98		
	Slope: −0.00008/(μL/L)				
jimson weed (*Datura stramonium*)					
1.	300	--		@ 35 days	Carlson and Bazzaz (1980)
	600	--	1.74		
	1200	--	1.96		
	Slope: 0.00097/(μL/L)				
pigweed (*Amaranthus retroflexus*)					
1.	380	--		@ 35 days	Carlson and Bazzaz (1980)
	600	--	1.41		
	1200	--	1.21		
	Slope: 0.00015/(μL/L)				

(continued)

Appendix C Continued.

	CO_2 conc. (μL/L)	Yield	Yield ratios	Comment (No. Obs.)	Investigators
ragweed (*Ambrosia artemisiifolia*)					
1.	300	–		@ 35 days	Carlson and Bazzaz
	600	–	1.10		(1980)
	1200	–	1.24		
	Slope: 0.00026/(μL/L)				
velvetleaf (*Abutilon theophasti*)					
1.	350	35.34		@ 45 days	Patterson and Flint
	600	47.96	1.36		(1980)
	1000	54.34	1.54		
	Slope: 0.00080/(μL/L)				
2.	300	–		@ 45 days	Carlson and Bazzaz
	600	–	1.44		(1980)
	1200	–	1.75		
	Slope: 0.00079/(μL/L)				

APPENDIX D

Results of individual CO_2 enrichment experiments with woody species. The details are presented only for those experiments which maintained controlled CO_2 concentrations of 1200 μL/L or less for the duration of the experiment. The yield ratio range and the number of observations are presented for other experiments which did not meet these criteria. The slopes are the rate of change of yield ratio with CO_2 concentration. The yield units are grams dry weight per plant unless otherwise noted.

	CO_2 conc. (μL/L)	Yield	Yield ratios	Comment (No. Obs.)	Investigators
blue spruce (*Picea pugens*)					
1.	250–400	10.84		@ 12 months	Tinus (1972)
	1100–1300	15.85	1.46		
	Slope: 0.00053/(μL/L)				
cottonwood (*Populus deltoides*)					
1.	300	–		@ 35 days	Carlson and Bazzaz
	600	–	1.65		(1980)
	1200	–	1.74		
	Slope: 0.00073/(μL/L)				
crabapple (*Malus toringoides*)					
1.			1.57	(1)	Krizek et al. (1971)
ponderosa pine (*Pinus ponderosa*)					
1.	250–400	12.35		@ 12 months	Tinus (1972)
	1100–1300	18.24	1.48		
	Slope: 0.00055/(μL/L)				
scots pine (*Pinus silvestris*)					
1.			2.00	(1)	Alden (1971)
silver maple (*Acer saccharinum*)					
1.	300	–		@ 35 days	Carlson and Bazzaz
	600	–	1.61		(1980)
	1200	–	1.89		
	Slope: 0.00091/(μL/L)				
sycamore (*Platanus occidentalis*)					
1.	300	–		@ 35 days	Carlson and Bazzaz
	600	–	1.13		(1980)
	1200	–	1.30		
	Slope: 0.00033/(μL/L)				
white pine (*Pinus strobus*)					
1.	300	4.1		cm height	Funsch et al. (1970)
	1000	9.2	2.24	@ 4 months	
	Slope: 0.00177/(μL/L)				

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