Perspective on the relative insignificance of increasing atmospheric CO₂ concentration to crop yield

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Abstract

Average yield of most crops in many countries increased significantly during the past 50 to 100 years. Although atmospheric CO₂ concentration, [CO₂]₀, also increased during that time period, and although crop growth and yield can respond positively to [CO₂]₀ increase, yield increases were due mainly to factors other than increasing [CO₂]₀. Similarly, some yield increases prior to 1900 were also associated primarily with factors other than changes in [CO₂]₀. In particular, past national average yield increases were the result chiefly of technological advances such as nitrogen fertilization; selection of genotypes with increased harvest index and disease resistance; mechanization of planting, cultivation, and harvesting; and chemical weed and pest control. If technology continues to increase average yields at recent rates, near-future increases in [CO₂]₀ will have only small impacts on yield in comparison to technology in many countries. Conversely, if future increases in [CO₂]₀ are the main drivers of future yield increases, those yield increases will be small. These points are demonstrated through a comparison of (i) long-term records of yield, (ii) data from key controlled-[CO₂] experiments, and (iii) records of past [CO₂]₀. Finally, it is noted that continued [CO₂]₀ increase may bring with it climatic changes that could have negative or positive impacts on future yield.

Keywords: Atmospheric CO₂ concentration; Crop yield; Hay; Oryza; Rice; Triticum; Wheat; Yield improvement

1. Introduction

Earth’s atmospheric CO₂ concentration, [CO₂]₀, increased about 30% during the past 200 years, from near 280 to more than 360 ppm (v/v) (Fig. 1). Although it is impossible to accurately predict future [CO₂]₀, it could reach 600–800 ppm during the next 100 years (Walker and Kasting, 1992). This is of concern because increasing [CO₂]₀ may be warming the Earth’s surface and could alter temporal and spatial patterns of precipitation and evaporation due to an enhanced global ‘greenhouse effect’ (e.g. Karl et al., 1997). Any climatic changes associated with increasing [CO₂]₀ have the potential to affect crop physiol-

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Global mean land surface air temperature increased slightly (<1°C) during the past 100 years (Jones, 1994). Moreover, on 8 January 1998, the U.S. National Oceanic and Atmospheric Administration announced that 1997 was globally the warmest year on record (since 1880). Further, the five warmest years all occurred since 1990. This warming trend could be related (in part) to increasing [CO₂]₀.

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For example, warming might alter rates of photosynthesis and photorespiration (and decrease their ratio), increase respiration rates, alter rates of biosynthesis (growth), and accelerate phenological development. Increased temperature and/or altered patterns of precipitation could also modify the timing of sowing and/or the geographic distribution of some crops. It is significant that both the duration of kernel growth and yield of the major grain crops can be negatively related to temperature (e.g. Fischer, 1983; Evans, 1993), although reduced frequency of frosts associated with warming might enhance yield in some circumstances (Nicholls, 1997).

The other ‘half’ of the ‘CO2 issue,’ increasing \([\text{CO}_2]_a\) per se rather than any associated climatic changes, is expected to stimulate crop growth and yield, and more so in \(C_3\) compared with \(C_4\) species (Lawlor and Mitchell, 1991; Rogers et al., 1994). This is due, in part, to the facts that (Lawlor, 1995): (i) canopy photosynthesis is a main driver of crop growth, (ii) \(C_3\) photosynthesis is not \(\text{CO}_2\)-saturated at present \([\text{CO}_2]_a\), and (iii) \(\text{CO}_2\) inhibits photorespiration, which is more prevalent in \(C_3\) than in \(C_4\) plants. In addition, elevated \([\text{CO}_2]_a\) may increase crop water-use efficiency (Rogers et al., 1994) and might slow respiration rate per unit plant dry mass (Amthor, 1997) in both \(C_3\) and \(C_4\) crops. Consequently, future crops will be affected by increasing \([\text{CO}_2]_a\) itself, usually in a positive way. Moreover, past increases in \([\text{CO}_2]_a\) are probably already enhancing yields to some extent.

Quantifying the magnitude of yield responses to changes in \([\text{CO}_2]_a\) is a present research challenge (e.g. Pinter et al., 1996), with a significant amount of empirical evidence indicating a 20–50% increase in growth of many crop species with a doubling of present \([\text{CO}_2]_a\) (e.g. Kimball, 1983; Lawlor and Mitchell, 1991). It is important to note that the \(\text{CO}_2\) responses of photosynthesis and plant growth are asymptotic, so the gain in yield per unit \([\text{CO}_2]_a\) increase declines as \([\text{CO}_2]_a\) increases (Lloyd and Farquhar, 1996).

The goal of this paper is to assess the role of increasing \([\text{CO}_2]_a\) in crop yield improvement. The analysis is based mainly on historical \([\text{CO}_2]_a\)s, historical British wheat yields, results from a subambient \([\text{CO}_2]_a\) experiment with wheat, and results from superambient \([\text{CO}_2]_a\) field experiments with wheat. British wheat yield is the focus due to the length of the historical yield record, but other wheat yield data, rice yield data, and hay yield data are also considered. The following two questions provide the framework for this paper:

1. Did the about 30% (more than 80 ppm) increase in \([\text{CO}_2]_a\) since 1800 play a significant role in past crop yield increases?
2. Will further \([\text{CO}_2]_a\) increases significantly enhance future crop yield compared to enhancements possible from improved technology?

My short answer to the first question is No, and to the second is Probably not. The remainder of this paper provides support for these answers.

An important underlying assumption of this discussion is that increasing \([\text{CO}_2]_a\) has a direct stimulatory effect on crop yield. It is also possible that future increases in \([\text{CO}_2]_a\) will limit yield of some crops in some regions through related climatic changes, as mentioned above, and this possibility should not be
dismissed lightly. The impact of increasing [CO₂] on those crops would be negative.

2. British wheat yield from 1200 to 1800

British wheat yield estimates for the period 1200–1800 come mainly from statistics for a few manors and the opinions of experts recorded at the time. Available values are in some cases anecdotal, and uncertainty in many estimates is large (see also 4). As a result, many yield values between 1200 and 1800 are difficult to substantiate, and national averages are impossible to know with certitude. But in spite of uncertainties, a
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*a* Years are approximate in some cases.

*b* See Footnote 4 concerning units conversions.

*c* Averages were calculated for manors with more than 20 years’ data.
consideration of British wheat yield during the period 1200–1800 (Table 1) is important because $\text{[CO}_2\text{]}_a$ was relatively well characterized then (Fig. 1; and references in Etheridge et al., 1996) and any yield trends that are evident during that period might be used to assess past crop responses to $\text{[CO}_2\text{]}_a$ relative to other factors influencing yield.

Possibly the most thorough investigation of British crop yield trends before 1350 is Titow’s (1972) analysis of the bishopric of Winchester manor records. That analysis is limited to the bishopric of Winchester manors rather than all of Britain, but it nonetheless indicates a relative constancy of wheat yield between 1209 and 1350, with large year-to-year variation (e.g. Appendix N in Titow, 1972). Later wheat yield on the Winchester manors, for 82 individual years in the period 1350–1453, was compared to the average for the same period by Farmer (1991). My statistical analysis (details not shown) of that relative yield data indicates an about 5% increase in yield from 1350 to 1380 (with much year-to-year variation) followed by an about 10% decline in yield from 1380 to 1453. Wheat yield on seven manors in Essex and Hertfordshire showed no obvious trend in yield between 1300 and 1410, with perhaps an earlier decline between 1270 and 1300 (Farmer, 1983; see Table 1). On the Prior of Norwich’s manor at Martham in Norfolk, reported mean yield in the period 1300–24 was a high 113 g m$^{-2}$, which dropped to 69 g m$^{-2}$ in the period 1400–24 (Campbell, 1983). A large decline in yield on this single manor was likely the result mainly of significant reductions in labor for weeding, manuring, and harvesting during the latter period (Campbell, 1983). Based on these few data, British wheat yield during the period 1209–1424 was stable, or perhaps declining slightly. During that same period, $\text{[CO}_2\text{]}_a$ was stable, or declining slightly (less than 1%, Fig. 1), and I conclude that nothing can be confidently said about effects of $\text{[CO}_2\text{]}_a$ on wheat yield in this period because (i) the $\text{[CO}_2\text{]}_a$ data are not precise enough, (ii) the yield data are limited in extent and credibility, and (iii) the apparent changes in both are small.

English weather during the early 1500s was ‘normal,’ but from 1540 to 1600 it was ‘frequently rainy and bad’ (Curtler, 1909 p. 89) which presumably limited yield. In spite of this, the only yield estimate in Table 1 for the early 1500s (44–55 g m$^{-2}$ in 1500) was exceeded by estimates for later that century (62 g m$^{-2}$, 1560–69; 101–134 g m$^{-2}$, 1570–80) and for 1600 (88 g m$^{-2}$). Between ca. 1565 and 1695, wheat yield may have increased from about 62 to 76 g m$^{-2}$ in Hertfordshire (Glennie, 1988). This overall apparent 23% increase in yield occurred while $\text{[CO}_2\text{]}_a$ declined a few percent (Fig. 1). Again, uncertainty in data preclude firm conclusions about effects of $\text{[CO}_2\text{]}_a$ changes on British wheat yield trends from 1500 to 1700, although the evidence available indicates $\text{[CO}_2\text{]}_a$ declined whereas yield increased.

Most historians concerned with the topic are convinced that British average wheat yield increased between 1700 and 1800, although the magnitude of the increase is uncertain. Some of the yield values shown in Table 1 for that period have been criticized. For example, Holderness (1989) purported that the “eighteenth-century data presented by Bennett are too pessimistic.” On the other hand, Holderness (1989) proposed that “yields given by Young in his tours around 1770…are certainly too high [to be average values] for that period,” an opinion also expressed by others (Turner, 1982).

Wheat yields on the Isle of Wight for 15 years in the period 1732–50 show a significant upward trend (Fig. 2). During the same period, $\text{[CO}_2\text{]}_a$ increased less than 1 ppm, which could hardly explain any of the yield increase. But, the yield record may be too short to be meaningful in that respect. In any case, it gives an indication of likely year-to-year variation in the yield in that area during the mid-1700s. Year-to-year variation in national average yield can also be large, and this must be considered when evaluating the significance of a yield estimate associated with a particular year. For example, Turner (1982) states that “there was a good average harvest in 1793, but 1794 was below average, and so was 1795.” The English average yield between 1790 and 1800 was supposed to be about 131 g m$^{-2}$ whereas the 1794 and 1795 yields in England were estimated at 113 and 105 g m$^{-2}$, respectively (Table 1). Note that Isle of Wight wheat yield during the period 1732–50 (Fig. 2) generally exceeded the proposed 1790s ‘average year’ English average yield of 131 g m$^{-2}$.

The overall trend I perceive from Table 1 and the discussion above is that prior to ca. 1500, average British wheat yield was much less than 100 g m$^{-2}$, but by ca. 1700 yields of 100 g m$^{-2}$ were common, and during the 1700s average yields often exceeded
100 g m\(^{-2}\). By 1800, average yield may have been about 150 g m\(^{-2}\) (Holderness, 1989). Thus, perhaps, more than a doubling of average yield occurred between 1200 and 1800, whereas \([\text{CO}_2]_a\) was no greater in 1800 than it was in 1200 (Fig. 1). This indicates that \([\text{CO}_2]_a\) had no bearing on the significant long-term average yield increase between 1200 and 1800. Causes of yield increases between 1200 and 1800 – and proposed setbacks and limitations to yield increases – are often discussed (e.g. Percival, 1934; Jones, 1967, 1974; Turner, 1982, 1986; Campbell, 1983; Thirsk, 1985; Outhwaite, 1986; Glennie, 1988; Beckett, 1990). I am not concerned here with outlining all the causes of yield increase between 1200 and 1800, but rather evaluating whether \([\text{CO}_2]_a\) influenced the yield trend. It apparently did not.

3. British wheat yield since 1800

3.1. The first decade

A mean yield of 152 g m\(^{-2}\) for British wheat is given for 1801 by Turner (1982). In a summary of data from 116 English parishes in 1801, Turner (1986) gives a mean yield of about 124 g m\(^{-2}\) in open fields compared to 153 g m\(^{-2}\) in enclosed fields. Wheat yield of about 135 g m\(^{-2}\) on ‘good fallow land’ in 1805 at Hereford is listed by Curtler (1909, p. 246), and British average yield may have been about 155 g m\(^{-2}\) by 1810 according to Holderness (1989).

3.2. An 1815–59 areal survey of wheat yield

Estimates of British wheat yield each year in the period 1815–59 are given in Healy and Jones (1962). The 1815–20 values in that dataset are supposed to reflect ‘national averages’ (Healy and Jones, 1962). Yield in the period 1821–59 is from an extensive areal survey of farms throughout England and Wrexham, Wales. It was proposed that yield for the period 1821–59 in that dataset may overestimate the British average yield because “it seems likely that surveyors visited the more cooperative farms, and that on these the yield tended to be higher than average” (Healy and Jones, 1962). In fact, however, there is no significant discontinuity in yield at 1821 in the dataset and the average yield in the period 1815–20 exceeds the average in the period 1821–26 in the Healy and Jones (1962) dataset (Fig. 3). According to Adams (1932), British grain (not just wheat) harvests (yield times area) in 1813, 1815, 1819, and 1820 were large, but harvests were poor in 1809, 1810, 1811, and 1812. A comparison can be made to wheat yields given by
Healy and Jones (1962) from 1815 onwards for a preliminary check on consistency among sources. Indeed, Healy and Jones (1962) list large wheat yields in 1815 and 1820, but only a modest yield in 1819. Adams (1932) also notes that national grain harvests were poor in 1828–30, which is consistent with low wheat yield in 1828 and 1829 given in Healy and Jones (1962), but not the moderate 1830 wheat yield they list.

The Healy and Jones (1962) data indicate stable British wheat yield from 1815 to the late 1830s, followed by a rapid increase through the early 1840s, followed by stable yields to 1859, with significant year-to-year variation throughout the record (Fig. 3). Holderness (1989), however, claims that “yields cited by Jones and Healy... overstate the true position” and that “the ascent of yields from 1815–20 to 1845–50 by 45 per cent [in the Healy and Jones dataset] is too precipitate” based on other analyses of wheat yield during that period. Moreover, Holderness (1989) justifies a national average yield of about 190 g m\(^{-2}\) ca. 1850, which is much less than values given by Healy and Jones (1962) for that time (Fig. 3).

Throughout the period 1815–59, corresponding to the Healy and Jones (1962) dataset, [CO\(_2\)]\(_a\) was little changed (Fig. 3). Thus, if the Healy and Jones (1962) dataset reflects the true relative yield increase even on just the survey farms, most of that increase cannot be attributed to increasing [CO\(_2\)]\(_a\). Holderness (1989), however, puts the British average wheat yield gain from 1800 to 1850 at only about 40 g m\(^{-2}\) (increase from 150 to 190 g m\(^{-2}\)). Nonetheless, this 27% increase in yield proposed by Holderness (1989) for the period 1800–50 occurred as [CO\(_2\)]\(_a\) increased only about 3 ppm (1%; Fig. 1), implying that [CO\(_2\)]\(_a\) increase had little to do with the proposed yield gain during that 50-year period.

### 3.3. Since 1852

British average wheat yield in the period 1852–65 is tabulated in Percival (1934) p. 54. Those values are from Lawes and Gilbert. Percival (1934) pp. 54–55 also lists yield for the period 1866–1932 from the Ministry of Agriculture’s Agricultural Statistics. Yield in the period 1852–84 from Percival (1934) is used in this analysis (Fig. 4); post-1884 data are taken from other sources (see below). A comparison of Figs. 3 and 4 reveals a large discrepancy between yields summarized in Healy and Jones (1962) and in Percival (1934). The datasets overlap for the period 1852–59, with the Percival (1934) (i.e. Lawes and Gilbert) mean yield for that overlap period only 52% of the Healy and Jones (1962) mean yield. The Percival (1934) data
are broadly consistent with the analysis of Holderness (1989) and British government statistics.

From 1852 to 1884, British wheat yield declined about 7.4% according to a regression analysis of data in Percival (1934), although the slope is not statistically significantly different than zero (not shown). At the same time, \([CO_2]_a\) increased nearly 7 ppm (2.4%; Fig. 4). Thus, that increase in \([CO_2]_a\) did not stimulate British average wheat yield.

British average wheat yields for the period 1885–1966 were published by the Ministry of Agriculture, Fisheries and Food (1968). Between 1885 and 1947, yield change paralleled \([CO_2]_a\) change (Fig. 5). During that 62-year period, yield increased about 14% as \([CO_2]_a\) increased from about 292 to 311 ppm (or 6.4%). The theoretical analysis of Lloyd and Farquhar (1996) indicates a 6–7% increase in C3 plant growth with a \([CO_2]_a\) increase from 292 to 311 ppm at 20°C (see their Fig. 3 for lines associated with respiration/photosynthesis ratios of 0.3 and 0.5). Thus, perhaps half the yield increase between 1885 and 1947 – when yield increase was slow – was due to concomitant \([CO_2]_a\) increase. But later, between 1947 and 1966, British average wheat yield increased more than it had between 1885 and 1947 whereas \([CO_2]_a\) increased only about half as much as it did during the period 1885–1947 (Fig. 1). Therefore, no more than a small fraction of the yield gain from 1947 to 1966 was likely due to increasing \([CO_2]_a\).

British average wheat yield during the period 1967–96 was published in the FAO annual Production Yearbooks. As it was during the period 1948–66, the rate of increase of British average wheat yield after 1966 was rapid, and this was accompanied by a more modest \([CO_2]_a\) increase (Fig. 6). As shown below, the post-1947 period is one during which \([CO_2]_a\) increase played at most a minor role in British average wheat yield gain. It is also the period of most significant yield increase.

It is worth noting that the area of land sown with wheat in Britain was not constant, but changed with time. The change in area of wheat itself may influence average yield, because a change in total area can be accompanied by a change in the ratio of ‘productive’ to ‘marginal’ land. For example, if prices are low, marginal land might be released from production, resulting in an increase in the average yield without any change in yield on the remaining productive land.

In the 1852–84 data (Percival, 1934), high average yield years occurred with relatively small area in wheat and, conversely, low average yield years occurred with large area in wheat. This confounds any relationship between trends in average yield and changes in \([CO_2]_a\). Moreover, during the period ca.
1850–1930, the area of wheat grown in Britain decreased about 60% (Percival, 1934). It is likely that less productive land was taken out of wheat at a greater rate than productive land, with the result that mean yield increased due to changes in the mean quality of land used for wheat production (Percival, 1934). Changes in the area of wheat grown could easily have been more important to British yield trends from 1850 to 1930 than was the coinciding 22 ppm (about 8%) increase in \([\text{CO}_2]\).
4. A subambient controlled-[CO₂] experiment with wheat: Comparing experimental data to past yield trends

I surmise above that British average wheat yield increases during several periods since 1800 are too large to be accounted for by the concomitant [CO₂]a increase. The most pertinent available experimental data shedding light on this issue come from the study of Mayeux et al. (1997). They grew wheat in a 38 m long chamber inside a glasshouse. Air moved through the chamber from one end to the other. During the daytime, CO₂ uptake by the plants in the chamber reduced the [CO₂] of the air as it passed through the chamber, creating a subambient [CO₂]a gradient (Mayeux et al., 1997). The daytime [CO₂]a gradient was maintained by varying the air flow rate through the chamber in response to changes in incident light. The mean daytime [CO₂]a near the plants at the chamber entrance was about 345 ppm and the value near plants at the chamber outlet was about 205 ppm (see, e.g. Fig. 3 in Mayeux et al., 1997). Nighttime [CO₂]a increased along the length of the chamber, due to CO₂ release from plants and soils, but the gradient was kept small by a rapid air flow rate. A photograph of the chamber is in volume 104/105 of *Vegetatio* (1993, p. 156).

Mayeux et al. (1997) grew two wheat cultivars, Yaqui 54 and Seri M82, with two soil moisture treatments. Yaqui 54 is an older tall cultivar and Seri M82 is a newer semidwarf cultivar. Water was added weekly to all plants during the first 50 days of the 100-day 'growing season,' but half the plants of each cultivar received no additional water during the second 50 days (water stress treatment). This water stress treatment is particularly important because one of the proposed main benefits of increasing [CO₂]a for crops is increased water-use efficiency (Rogers et al., 1994). Suffice it to say here that, contrary to expectations, yield differences can be attributed solely to differences in [CO₂]a. In the ‘real world,’ however, many other factors changed as [CO₂]a increased during the past two centuries. The other factors include several components of crop advancement such as genetic improvement and increased fertilizer use. The fraction of past national average yield increase due to past [CO₂]a increase can be estimated by dividing the relative yield increase in a controlled-[CO₂] experiment (over a given [CO₂]a range) by the relative yield increase seen in actual crops during the period experiencing that same range of [CO₂]a. This approach is used in the following subsection to assess the role of [CO₂]a increase on past British wheat yield increases. The experimental results of Mayeux et al. (1997) represent the ‘all factors but [CO₂] unchanged’ case.

4.1. Historical British wheat yield

By pooling British wheat yield estimates between 1800 and 1996 from Holderness (1989); for an 1800 and an 1850 estimate, Percival (1934), Ministry of Agriculture, Fisheries and Food (1968), and FAO (1969–1996), a 196-year record is obtained. A comparison of that 196-year record to wheat yield responses to subambient [CO₂]a obtained by Mayeux et al. (1997) shows that the relationship between historical British wheat yield and actual [CO₂]a is much stronger than the relationships between yield and [CO₂]a in the controlled-[CO₂] experiments (Fig. 7). A comparison of the left-most British wheat yield value in Fig. 7 (yield ca. 1800) to the 1996 yield indicates a 440% increase in yield over that 196-year period. According to the cubic smoothing spline in Fig. 1, the period 1800–1996 corresponds to the [CO₂]a range of 281.8–362.6 ppm. Over that same [CO₂]a range, yield of well-watered Seri M82 would increase only about 54% according to the regression equation in Mayeux et al. (1997). Yield increases over that same [CO₂]a range for well-watered Yaqui 54, water-stressed Seri M82, and water-stressed Yaqui 54 would be about 57, 30, and 44%, respectively. Thus,

5Wheat yield from Healy and Jones (1962) is not included in this pooling of data because it departs from other estimates of British national average yields. That is, I assume that yield estimates by Holderness (1989) are more accurate than data in Healy and Jones (1962).
about 12, 13, 7, and 10% (for an average of 10.5%) of the British wheat yield increase since 1800 might be attributed to concomitant [CO$_2$]$_a$ increase based on the experimental data of Mayeux et al. (1997).

Moreover, British wheat yield did not parallel [CO$_2$]$_a$ during the past 200 years (Fig. 7). Instead, yield increase occurred mainly since ca. 1947, when the trend in yield departed significantly from the trend in [CO$_2$]$_a$. Yield increases since ca. 1947, when [CO$_2$]$_a$ reached about 311 ppm, are nearly nine times greater than expected according to the well-watered Yaqui 54 (i.e. the best case) results of Mayeux et al. (1997). This is not to say that British wheat did not respond positively to [CO$_2$]$_a$ over the past 200 years, for it probably did. Indeed, the diminutive increases in British wheat yield between ca. 1905 and 1945 that occurred as [CO$_2$]$_a$ increased from about 297 to 311 ppm might be due to the concomitant [CO$_2$]$_a$ increase, as indicated by Fig. 7. Nonetheless, other factors were, at least in their sum, evidently much more important than [CO$_2$]$_a$ increase was to the bulk of post-1800 British wheat yield gain.

4.2. A revision of Monteith’s analysis of British wheat yield

As part of a classic theoretical study of environmental constraints on British crop growth, Monteith (1977) estimated the role of increasing [CO$_2$]$_a$ in British yield increase. He reckoned that about 21% of the increase in wheat yield during the decade 1966–75 was due to concurrent [CO$_2$]$_a$ increase (see 10 left-most data in Fig. 6). A new look at his analysis, however, indicates a smaller effect of [CO$_2$]$_a$ increase on recent British wheat yield increase.

Monteith (1977) proposed that growing season [CO$_2$]$_a$ might increase from 320 to 400 ppm between 1976 and 2000, and according to his crop growth model, this increase could stimulate yield by about 11%. Such a gain in yield over that [CO$_2$]$_a$ range is consistent with empirical data (e.g. Kimball, 1983). The present trend in global [CO$_2$]$_a$, however, indicates that [CO$_2$]$_a$ may not exceed 370 ppm by 2000, which reduces the theoretical growth stimulation between 1976 and 2000 to about 7%. A linear regression of
British average wheat yield over the period 1966 to 1996 results in a 14.8 g m^-2 gain per year. For the period 1976–2000, the same regression equation predicts that British wheat yield would increase about 355 g m^-2 or nearly 71% of the 1976 value. Thus, if increasing [CO₂]a causes a 7% yield gain between 1976 and 2000, and the total gain is 71%, just under 10% of the total gain will be due to [CO₂]a increase. This is less than half that proposed by Monteith (1977) for the decade 1966–75.

The overestimation by Monteith (1977) of the role of [CO₂]a increase on gains in British average wheat yield stemmed in part from his somewhat pessimistic (in hindsight) view of British wheat yield trends. He speculated that it might take until about 2010 for British average wheat yield to reach 745 g m^-2, but that value was already exceeded in 1984 (772 g m^-2), 1992 (801 g m^-2), 1995 (770 g m^-2), and 1996 (811 g m^-2), the last year of data at the time of writing. Moreover, the other years since 1990 all produced average yields approaching the 745 g m^-2 ‘target’ (i.e. 725 g m^-2 in 1991, 733 g m^-2 in 1993, and 735 g m^-2 in 1994).

### 4.3. Historical United States wheat yield

Mayeux et al. (1997) regressed average U.S. wheat yield on [CO₂]a for the period 1866–1989 (see their Fig. 9) and found that the relationship was statistically significant. They went on to suggest that their experimental and statistical analyses indicated that “rising CO₂ concentration has accounted for 19–48% of the observed increase in average yields of wheat in the U.S. over the last few decades.” A reexamination of their argument, however, indicates that it is amiss.

According to Mayeux et al. (1997), U.S. wheat yield increased from 135 to 260 g m^-2 from 1955 to 1990, as [CO₂]a increased from 312 to 352 ppm. This is an absolute increase of 125 g m^-2, but more importantly, it is a 92.6% relative increase. Mayeux et al. (1997) then compared this gain of 125 g m^-2 to the absolute increases in yield in their subambient [CO₂]a experiments over the 312–352 ppm [CO₂]a range. The absolute yield gains in their experiment are only germane to U.S. average yields, however, if their experiment reflects U.S. average yield, which it does not (compare yield in their Figs. 3 and 9 at a [CO₂]a of 312 ppm). Such a comparison of absolute yield increases is therefore irrelevant to an analysis of the effect of past [CO₂]a increase on U.S. wheat yield.

A better method is to compare the relative gains in yield in their experiments to the relative gains in average U.S. yield over the 312 to 352 ppm [CO₂]a range. This normalizes the results to a common baseline yield of 100% at a [CO₂]a of 312 ppm. But what does this better method indicate? The relative gains in their experiments for water-stressed Seri M82 and Yaqui 54 over the 312–352 ppm [CO₂]a range were 13.4 and 18.7%, respectively. The relative yield gains for well-watered Seri M82 and Yaqui 54 were 22.3 and 23.3%, respectively. Thus, the relative gain with respect to [CO₂]a increase in their experiment as a fraction of the relative gain in average U.S. wheat yield over the 312–352 ppm [CO₂]a range is 14.5, 20.2, 24.1, and 25.2%, which is in every case significantly smaller than the ‘fully a third, 33%’ they claimed (Mayeux et al., 1997 p. 277). The fraction of U.S. wheat yield gain between 1955 and 1990 that can be attributed to [CO₂]a increase is only about 21% according to their controlled-[CO₂] data and their approach of averaging the well-watered and water-stressed plant data. This is, however, still large compared to relative gains in British wheat yield attributable to [CO₂]a increase during the same period. The cause of the difference in the fraction of past wheat yield gain in Britain and the U.S. attributable to [CO₂]a increase is the larger relative gain in British yield since 1955.

### 4.4. Historical Australian wheat yield

While Monteith (1977) probably overstated the effects of recent [CO₂]a increase on British wheat yield gain, and Mayeux et al. (1997) apparently inflated the effects on U.S. wheat yield, Nicholls (1997) may have understated the relative effect of recent [CO₂]a increase on Australian wheat yield. Nicholls (1997) compared year-to-year changes in Australian wheat yield with year-to-year changes in [CO₂]a at Mauna Loa Observatory during the period 1958/9–1991/2. There were only statistically insignificant relationships, which Nicholls (1997) interpreted as indicative of only small (if any) effects of increasing [CO₂]a on yield. But, year-to-year changes in [CO₂]a at Mauna Loa Observatory need not reflect year-to-year changes in Australia because there is a small
discrepancy between patterns of [CO₂]a in the northern (Mauna Loa) and southern (Australia) hemispheres [see Footnote 6]. Moreover, year-to-year changes in [CO₂]a are so small – an average of less than 0.4% per year at Mauna Loa from 1958 to 1991 – that they are trivial with respect to year-to-year changes in crop growth. On the other hand, the overall increase in [CO₂]a from 1958 to 1991 was about 40 ppm (almost 13%), which is sufficient to cause an increase in yield, albeit a small one (Kimball, 1983; Lloyd and Farquhar, 1996). That is, effects of [CO₂]a on yield are included in the longer term yield trend rather than in year-to-year yield variation.

But what might be the effect of past increases in [CO₂]a on Australian wheat yield? According to Nicholls (1997), Australian average wheat yield increased about 45% between 1952/3 and 1991/2. According to Fig. 1, [CO₂]a increased from 311 to 356 ppm between 1952 and 1991. According to linear regression equations in Mayeux et al. (1997) from their subambient controlled-[CO₂] experiments, an increase in [CO₂]a from 311 to 356 ppm increased wheat yield about 14.9, 20.8, 24.8, and 25.8% (in their four experiments). Thus, it might be expected that 33–57% of the increase in Australian average wheat yield during the period 1952/3–1991/2 resulted from increasing [CO₂]a. This relative effect of [CO₂]a increase on Australian wheat yield is large, in comparison to effects on British and U.S. wheat, because the gain in Australian average wheat yield since 1950 was comparatively modest.

4.5. Timing of yield increase with respect to [CO₂]a increase

If increasing [CO₂]a was a major cause of past wheat yield increase, it would be expected that the timing of yield increase would be about the same everywhere because [CO₂]a increase is global⁶. Not only would the yield increase have a similar time course in all countries, but that time course would track the [CO₂]a increase. This was not, however, the case, as revealed by an analysis of wheat yield trends since 1900 in 21 countries (Calderini and Slafer, 1998). Instead, significant variation in the time course of wheat yield increase since 1900 exists among countries (e.g. Fig. 1 in Calderini and Slafer, 1998). The timing of rice yield increase also varies by up to several decades among countries (e.g. Fig. 1.8 in Evans, 1993). That is, past yield increase in wheat (and rice) was not caused by a global phenomenon such as [CO₂]a increase, but by national factors such as knowledge dissemination, basic research, economics, and government policy. Moreover, Mexican wheat yield is apparently unchanged since ca. 1981 (Calderini and Slafer, 1998) even though [CO₂]a increase did not slow after 1981 (Fig. 1). And, between 1985 and 1995, when [CO₂]a increased as rapidly as during any other 10-year period since 1900, wheat yield may have been unchanged (or even declined) in Japan, the USA, Canada, Tunisia, Spain, and the former USSR (Calderini and Slafer, 1998). This too indicates an independence of yield trend from [CO₂]a increase. Similar evidence for a lack of control on yield by [CO₂]a increase is seen for U.S. maize. Between 1930 and 1980, U.S. average maize yield increased about 600%, but between 1980 and 1990 yield did not increase further (Fig. 1 in Duvick, 1992) even though the [CO₂]a increase continued. On the whole, therefore, the timing of yield increase since 1900 in the major grain crops both within and between countries is inconsistent with the notion that a global phenomenon such as [CO₂]a increase had a large impact on yield.

The analysis of on-farm wheat yield variability in the Yaqui Valley of Mexico during 1968–90 by Bell et al. (1995) may shed additional light on the role played by [CO₂]a increase on actual yield increases in recent decades. In particular, weather-adjusted yield gains from 1968 to 1990, which were estimated at 1.91% per year (Bell and Fischer, 1994), were partitioned as follows (Bell et al., 1995): 28% genetic (cultivar improvement); 48% increased nitrogen fertilization (probably brought about in part by a decline in fertilizer prices and by increase in grain price); and the remaining 24% ‘other factors.’ The other factors highlighted by Bell et al. (1995) as potentially contributing to yield improvement were increased farmer skill levels and phosphorus fertilizer, but ultimately that 24% of yield gain was unexplained. Based on knowl-

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⁶There is a small northern hemisphere–southern hemisphere gradient in [CO₂]a and there is also a seasonal cycle in [CO₂]a imposed on the year-to-year increase that is strongest at high northern latitudes (Conway and Tans, 1996). In spite of these geographical and seasonal differences, the increase in [CO₂]a during this century is a global phenomenon about equally expressed in all agricultural areas.
edge of crop responses to $[CO_2]_a$, it seems likely that $[CO_2]_a$ increase during the period (about 31 ppm or 9.6%) was a component of the unexplained 24% even though $[CO_2]_a$ is not mentioned in Bell et al. (1995). Stated another way, no more than 24% of the weather-adjusted yield increase in wheat in the Yaqui Valley in the period 1968–90 was due to increasing $[CO_2]_a$. Actual yield increase was only 55% of the weather-adjusted increase, however, and this was attributed to a small increase in average growing season temperature during the study period (Bell and Fischer, 1994). That is, the negative impact of increasing temperature – possibly a result of an increasing $[CO_2]_a$-caused climatic change – on actual yield was of greater magnitude than the ‘unexplained’ weather-adjusted yield increase possibly due (in part) to increasing $[CO_2]_a$ per se. In this case, therefore, the net effect of increasing $[CO_2]_a$ (i.e. physiology + climate) might have been a limitation on, rather than a stimulation of, yield increase.

5. Hay yield in long-term field experiments

The above discussion indicates that increasing $[CO_2]_a$ had only small effects on grain yield increase compared with yield gains due to technology during the past century for several crops in many countries. A recent analysis of data from five plots in the Rothamsted Long-term Continuous Hay Experiment addresses hay yield responses to $[CO_2]_a$ increase with technology held constant (Jenkinson et al., 1994). Two of the plots were unfertilized since 1856, one plot was unfertilized since 1863, one plot received 4.8 g N m$^{-2}$ each year (along with additions of P, K, Na, and Mg) since 1858, and one plot received 9.6 g N m$^{-2}$ each year (along with additions of P, K, Na, and Mg) since 1858. Atmospheric N deposition increased on all the plots since the start of the experiment. Twice a year since 1875 hay was cut and removed from all the plots. All the plots were unlimed and “there have been no long-term trends in botanical composition of any of these five plots during the present century” (Jenkinson et al., 1994).

For the period 1891–1992, during which $[CO_2]_a$ increased about 62 ppm or 21% (Fig. 1), hay yield did not increase (Barnett, 1994; Jenkinson et al., 1994). To quote Jenkinson et al. (1994), “there was no consistent trend which would indicate that increasing atmospheric CO$_2$ [concentration]... increased herbage yields in [the Park Grass Continuous Hay Experiment at Rothamsted].’’ Indeed, five of the nine trends relating hay yield to $[CO_2]_a$ were negative for the unfertilized plots and five of the six trends relating hay yield to $[CO_2]_a$ were negative for the fertilized plots (Table 3 in Jenkinson et al., 1994). Similarly, hay yield on the unfertilized Palace Leas meadow plot did not increase between 1897 and 1980 (Coleman et al., 1987) even though $[CO_2]_a$ increased about 43 ppm or 14% (Fig. 1) during that period. Apparently, hay yield increase depends on management rather than $[CO_2]_a$ increase for the conditions of these experiments.

6. Superambient controlled-$[CO_2]$ field experiments with wheat and future wheat yield

A first look at whether future $[CO_2]_a$ increases will have a large effect on future yield in comparison to effects of future technology and farmer skill might be had by comparing recent yield trends with yield increases caused by superambient controlled-$[CO_2]_a$ treatments of wheat in the field. The most advanced studies of field-grown wheat responses to superambient $[CO_2]_a$ are the free-air CO$_2$-enrichment (FACE) experiments in Arizona, USA (Kimball et al., 1995; Pinter et al., 1996). Briefly, the FACE approach involves the release of concentrated CO$_2$ upwind of an experimental plot. The released CO$_2$ is then mixed with the ambient air by turbulence and delivered to the plot by advection. A control algorithm determines how much CO$_2$ is released and locates the upwind release points. An advantage of the FACE approach compared to various chamber fumigation methods is that crop microclimate is nearly unaltered. In practice, FACE plots are also larger than most chambered plots. Photographs of wheat FACE plots in Arizona are on the cover of Global Change Biology (vol. 1, no. 6, Dec. 1995) as well as in Fig. 1 in Kimball et al. (1995).

In one set of FACE experiments, hard red semi-dwarf spring wheat (cv. Yecora Rojo) crops were exposed to about 370 and 550 ppm $[CO_2]_a$ during 2 years with ample nitrogen fertilization and two levels of irrigation (well-watered and water-stressed). As expected, elevating $[CO_2]_a$ from 370 to 550 ppm...
increased wheat growth, with yield in the well-watered plots enhanced 8 and 12% and yield in the water-stressed plots enhanced 21 and 25% in the 2 years (Kimball et al., 1995; Pinter et al., 1996). The observed increases in yield are consistent with model predictions (e.g. Lloyd and Farquhar, 1996). The greater relative yield gain due to elevated [CO₂]ₐ with water stress than without (Kimball et al., 1995; Pinter et al., 1996) is contrary to the results from the chamber study of Mayeux et al. (1997).

Controlled-[CO₂] experimental results are again compared to historical British wheat yield. The trajectory of past British wheat yield with respect to past [CO₂]ₐ increase greatly exceeds yield responses to controlled [CO₂]ₐ in the Arizona FACE experiments (Fig. 8). Based on this comparison, if increases in average yield and [CO₂]ₐ follow recent patterns, future [CO₂]ₐ increase will have only a small influence on future yield changes compared with other drivers of yield gain. If, on the other hand, technology and technology dissemination are approaching their limits with respect to yield increase, then increasing [CO₂]ₐ may be the main driver of any future yield increases, although such increases would then be small in comparison to historical yield increases. The importance of future [CO₂]ₐ increases to future yields will therefore depend in part on the effectiveness of technology in further improving yield. Since British average wheat yield is already near 800 g m⁻², future increases might be expected to be limited. Average wheat yield in many other countries, however, is presently only half (or less) that in Britain, so gains could be larger. In any case, future contributions of technology to yield increase are unknown, and future [CO₂]ₐ increases are uncertain, but present trends indicate a relatively limited role for [CO₂]ₐ in advancing future yield.

7. An analysis of Chinese rice yield increase since 1949

The graphical assessment of the relative role of past [CO₂]ₐ increase on British wheat yield (Fig. 7) can be applied to other crops. Similarly, data from other crops can be used to compare recent trends in yield with yield responses to future [CO₂]ₐ increase as done for British wheat above (Fig. 8). For example, I derived annual average rice yield in the People’s Republic of China during the period 1949–90 from data in Colby
et al. (1992) and used yield data given by FAO for the period 1991–96. FAO values are in good agreement with those in Colby et al. (1992) throughout the 1980s, so combining the datasets seems suitable. Rice yield response to subambient and superambient controlled-[CO₂] levels was taken from Baker et al. (1990), who used paddy culture within sunlit, controlled-environment chambers in Florida, USA.

Between 1949 and 1996, Chinese rice yield increased about 220% (Fig. 9). During that same time, [CO₂]ₐ increased from about 311 to 363 ppm (according to the cubic smoothing spline in Fig. 1). According to an interpolating equation for the controlled-[CO₂] experimental data (see Fig. 9), rice yield increased about 11.2% over that same [CO₂]ₐ range. The ratio of the relative yield increase in the controlled-[CO₂] experiments to the relative increase in Chinese average rice yield, both over the [CO₂]ₐ range of 311–363 ppm, is therefore 11.2/220 or about 5.1%. Thus, only about 5% of the actual increase in Chinese average rice yield during the period 1949–96 can be attributed to the concomitant [CO₂]ₐ increase if the experiment of Baker et al. (1990) is representative of rice in general. In other words, as with British wheat, the dramatic increase in Chinese rice yield during the past several decades is apparently due mainly to factors other than increasing [CO₂]ₐ, even though [CO₂]ₐ increase and average-yield increase are strongly correlated in both cases.

The potential for future Chinese rice yield increase due to [CO₂]ₐ increase can also be judged by a consideration of the Baker et al. (1990) data. According to the quadratic interpolating equation shown in Fig. 9 for the response of rice yield to controlled-[CO₂], yield increased 48% with a doubling of [CO₂] from 350 to 700 ppm. If present yield trends are maintained, such a yield increase could be obtained within several decades with little change in [CO₂]ₐ, although a nearly 50% yield increase due to a doubling of [CO₂]ₐ would still be significant.

8. Conclusions

Data considered in this paper indicate that past increases in crop yield were due chiefly to factors other than past [CO₂]ₐ increases. For example, significant increases in average yield of British wheat...
were apparently obtained prior to 1800 when [CO₂]ₐ was more or less constant. Thus, changes in [CO₂]ₐ played no role in those yield increases. Between about 1800 and 1945, however, British wheat yield increased only slightly, and during that period [CO₂]ₐ increase might explain a large fraction of that modest yield gain (see Fig. 7). But, since ca. 1945, British wheat yield increased dramatically, and only a small fraction of that increase can be attributed to direct effects of concurrent [CO₂]ₐ increase. Long-term hay experiments too indicate that past increases in [CO₂]ₐ had at most small direct beneficial effects on yield. And, a comparison of Chinese rice yield increases to concomitant [CO₂]ₐ increases since 1949 demonstrate that yield increase was mainly a result of factors other than [CO₂]ₐ change. Moreover, trends in wheat yield increase since 1900 in 21 countries were asynchronous in spite of the fact that [CO₂]ₐ increase was a global phenomenon. The timing of rice yield increase was also asynchronous among countries during the past several decades. In some cases, recent average yields have stabilized even though [CO₂]ₐ continued to increase. I therefore conclude that global [CO₂]ₐ increases during the past 200 years had relatively small effects on crop yield in many – and perhaps most – cases. Rather, farmers, agronomists, crop breeders, and other scientists are responsible for the bulk of past crop yield increases, and the answer to the first question posed in Section 1 is: The about 30% increase in [CO₂]ₐ since 1800 played a minor role in past crop yield increases.

Views on whether potential and/or attainable yield can be increased in the future differ significantly, and I will not attempt to answer the question. Will average yield of major crops increase significantly in the future due to improved technology and dissemination of existing and/or improved technology? Nonetheless, it is clear that average yield can be greatly increased for many crops in many regions with no change in potential yield, but whether that occurs may ultimately hinge on national and international policy rather than science and farming (Mann, 1997). Returning to the issue at hand – increasing [CO₂]ₐ and future crop yield – I conclude from the evidence reviewed herein that future [CO₂]ₐ increases will play only a minor role in future yield increases if technology and management continue to increase crop yields at nearly the present rates. Stated the other way around, in any cases for which future [CO₂]ₐ increase makes a significant direct contribution to yield increase, the overall increase in yield will be small. In addition, future yield increase due to future [CO₂]ₐ increase alone will almost certainly not keep pace with human population growth during the coming decades – science, technology, and proper public policy will be needed to match crop yield to future food needs. Finally, any effects of increasing [CO₂]ₐ on future climate could reduce as well as enhance crop yield.

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References


7For example, according to Evans (1994) “it is clear that the improvement of genetic yield potential shows little sign of approaching a plateau in most crops as yet; indeed, it is still accelerating in several.” On the other hand, Sinclair (1994) wrote that it is “likely that environmental and physiological limits to crop yields have been approached under experimental conditions unless additional increases in harvest index can be achieved.” In many crops, future large increases in harvest index may be unlikely.


FAO (Food and Agriculture Organization of the United Nations), Annual. Production Yearbook. FAO, Rome.


