

**EFFECTS OF ENRICHED CARBON DIOXIDE AND OZONE STRESS ON  
CANOPY REFLECTANCE AND GRAIN YIELD IN WINTER WHEAT <sup>1</sup>**

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**ABSTRACT**

An experiment was conducted during the spring of 1991 at USDA Beltsville Agricultural Research Center to evaluate the combined effect of carbon dioxide (CO<sub>2</sub>) and ozone (O<sub>3</sub>) on remotely sensed multispectral canopy reflectance and grain yields in winter wheat (*Triticum aestivum* L.). Plants were grown full-season (after dormancy to harvest) in the field in open-top chambers supplied with charcoal-filtered air (CF) or CF + 40 nl/l O<sub>3</sub> above ambient O<sub>3</sub> concentration (7 h/day, 5 day<sub>s</sub>/week) having CO<sub>2</sub> concentration of ambient (350 μl/l) or +150 μl/l CO<sub>2</sub> (12 h/day). The resultant seasonal 7 h O<sub>3</sub> concentration was 19 nl/l and 79 nl/l O<sub>3</sub>, for low and high O<sub>3</sub> treatments, respectively. Multispectral canopy reflectance was measured weekly from the early vegetative stages until maturation. The normalized difference vegetation index (ND), which was used to estimate the fraction of absorbed photosynthetically active radiation (FAPAR) and the absorbed PAR (APAR). Total final biomass and grain yield was obtained after harvest at physiological maturity. Tests of main effect of O<sub>3</sub> on ND was significant from the third week of treatment until maturation. Main effect of CO<sub>2</sub> on ND was not significant for all measurement dates. However, main effects of CO<sub>2</sub> and O<sub>3</sub> were significant for both biomass and grain yield. Accumulated APAR over the growing season was significantly lower for the high-O<sub>3</sub> treatments. Plants grown under CO<sub>2</sub> enriched air had significantly higher conversion efficiency (ε) of APAR into above ground dry biomass than plants grown under ambient CO<sub>2</sub> air. Conversion efficiency was significantly lower for the O<sub>3</sub> treatment with ambient CO<sub>2</sub> air. High-O<sub>3</sub> treatments had about 15 % less grain weight than low-O<sub>3</sub> treatments. Enriched CO<sub>2</sub> treatments had about 25 % more grain weight than ambient CO<sub>2</sub> treatments. Regression analysis showed that ND was responsible for up to 76% of the grain yield variation for winter wheat growing under the different air qualities.

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## INTRODUCTION

Studies of the relationship of canopy spectral reflectance of wheat and crop yield have been widely reported (Tucker, 1980; Pinter et al., 1981; Rudorff and Batista, 1990). Crop yield is the result of numerous environmental factors that affect plant growth and development and therefore canopy reflectance (Wiegand, 1984). Vegetation indices calculated from the reflectance of red ( $R_r$ ) and near-infrared ( $R_{nir}$ ) radiation, such as the normalized difference vegetation index ( $ND = [R_{nir} - R_r] / [R_{nir} + R_r]$ ), are approximately linearly related to the fraction of absorbed photosynthetically active radiation (FAPAR) (Prince, 1991). Daughtry et al. (1992) demonstrated that FAPAR can be estimated with ND data and that biomass production can be estimated as a function of accumulated absorbed PAR. These authors also pointed out that there is a linear relation between above ground dry biomass and accumulated absorbed PAR with different rates of above ground dry biomass production (efficiency conversion  $\epsilon$ ) for different crops (i.e.,  $C_3$  and  $C_4$  crops).

Atmospheric  $CO_2$  concentrations have increased over the past century from about 290  $\mu\text{l/l}$  to 350  $\mu\text{l/l}$  and an increase to levels of about 500  $\mu\text{l/l}$  is expected by the end of the coming 20 to 30 years as a consequence of the world-wide growth in fossil fuel consumption (Wuebbles et al., 1989). An enriched  $CO_2$  environment can cause  $C_3$  plants to increase photosynthesis, and there by result in an increase in biomass, green leaf area duration and grain yield (Kurpa and Kickert, 1989). Near infrared radiation (700-1300 nm) is strongly scattered by vegetation and therefore highly dependent on the amount of biomass (Daughtry et al., 1992).

Ozone is among the most phytotoxic pollutants in the atmosphere and its formation and effects have been extensively investigated (Mulchi et al., 1986, 1988; Kurpa and Kickert, 1989). Ozone stress on wheat causes leaf injury, and a decrease in biomass and grain yield (Slaughter et al., 1989). Leaf reflectance in the visible wavelength is increased due to the decrease of PAR absorption by leaf pigments as a consequence of the injury to leaves caused by  $O_3$  (Runeckles and Resh, 1975).

The objective of this study was to investigate the use of multispectral canopy reflectance data to estimate the effects on above ground biomass and grain yield in winter wheat grown in open-top chambers and exposed to enriched  $CO_2$  and  $O_3$  stress,

## MATERIALS AND METHODS

A field study using open-top chambers was conducted at USDA Beltsville Agricultural Research Center, near Beltsville, Maryland in 1991. Winter wheat (cv. 'Massey') was covered after dormancy break in late March with 3 m diameter open-top chambers (Heagle et al., 1973). Atmospheric treatments consisted of two  $CO_2$  (ambient, and + 150  $\mu\text{l/l}$   $CO_2$ ) and two  $O_3$  regimes (charcoal-filtered air (CF) and CF + 40  $\text{nl/l}$   $O_3$  above ambient  $O_3$  concentration) arranged in a 2x2 factorial design (RCB) with 4 replicates. The enriched  $CO_2$  treatments were applied 12 h/day (06:00-18:00 EST), 7 days/week and the + 40

nl/l O<sub>3</sub> treatments were imposed 7 h/day (09:00-16:00 EST), 5 days/week from late March until early June.

Canopy reflectance was measured weekly, weather permitting, from early vegetative stages until maturation. A four band radiometer (Exotech model 100-BX) with a 15° field of view was used to measure reflectance factors (RF) in the following bands: 450-520, 520-600, 630-690, and 760-900 nm. An hand held boom was used to support the radiometer at about 2.3 m above the canopy. Four readings of approximately 0.3 m<sup>2</sup> of the canopy were taken for each chamber and RF was transformed to the normalized difference vegetation index (ND).

The fraction of absorbed PAR (FAPAR) was estimated from the linear relationship between ND and FAPAR reported by Daughtry et al., (1992) where:

$$\text{FAPAR} = -0.205 + 1.254 \text{ ND} \quad (1)$$

Incident PAR (PAR<sup>o</sup>) was obtained from a meteorological station close to the experimental site and absorbed PAR (APAR) was estimated:

$$\text{APAR} = \text{FAPAR PAR}_o \quad (2)$$

Incident PAR within the chambers may have been over estimated due to the fact that the incoming radiation is slightly attenuated by the plastic of the chamber walls.

Accumulated APAR was computed by the summation of the daily APAR obtained through interpolation from the close to weekly ND measurements throughout the crop growing season.

The conversion efficiency ( $\epsilon$ ) is the dry matter: radiation quotient or the dry matter production per unit of absorbed PAR (g/MJ):

$$\epsilon = \text{Above ground dry biomass} / \text{Accumulated APAR} \quad (3)$$

Total final above ground dry biomass and grain yield were determined from three 0.64 m<sup>2</sup> samples from each chamber following plant maturation in mid June.

## RESULTS AND DISCUSSION

The seasonal 7-h average (09:00-15:00 EST) O<sub>3</sub> concentration for ambient air was 40 μl/l. The resultant 7-h averages for the high and low O<sub>3</sub> treatments were 79 μl/l and 19 μl/l, respectively.

The effects of CO<sub>2</sub> and O<sub>3</sub> on canopy reflectance measurements, transformed to the ND, are illustrated in Table 1. Significantly lower ND values for main effects on O<sub>3</sub> (79 nl/l) were observed from day of year 106 on, which was coincident with the first visual symptoms of O<sub>3</sub> injury on leaves in the O<sub>3</sub> treated chambers. The lower NDs observed in the high-O<sub>3</sub> treatments are likely the combined result of an increase in the reflectance in the red waveband caused by lower absorption of the incoming PAR by the leaf pigments and the lower near infrared canopy reflectance due to a significant decrease

Table 1

Summary of main and simple effects of CO<sub>2</sub> and O<sub>3</sub> treatments on the normalized vegetation index (ND) for measurement dates 1 to 11.

Chamber Treatments		D A Y O F Y E A R										
CO <sub>2</sub>	O <sub>3</sub>	92 (ND-1)	94 (ND-2)	100 (ND-3)	106 (ND-4)	113 (ND-5)	121 (ND-6)	126 (ND-7)	132 (ND-8)	136 (ND-9)	144 (ND-10)	151 (ND-11)
CO <sub>2</sub> Treatment Means												
Ambient	-	0.888	0.910	0.940	0.927	0.912	0.910	0.909	0.886	0.866	0.814	0.606
+150 µl/l	-	0.888	0.910	0.941	0.934	0.926	0.916	0.916	0.895	0.881	0.837	0.557
Statistical significance												
O <sub>3</sub> Treatment Means												
-	CF	0.889	0.909	0.940	0.936	0.939	0.934	0.925	0.903	0.887	0.851	0.618
-	CF+O <sub>3</sub>	0.887	0.911	0.940	0.926	0.889	0.893	0.899	0.878	0.859	0.800	0.566
Statistical significance												
					*	**	**	**	**	**	**	**
CO <sub>2</sub> and O <sub>3</sub> Treatments												
Ambient	CF	0.893	0.909	0.940	0.935 <sup>a</sup>	0.937 <sup>a</sup>	0.934 <sup>a</sup>	0.925 <sup>a</sup>	0.903 <sup>a</sup>	0.885 <sup>a</sup>	0.848 <sup>a</sup>	0.635
	CF+O <sub>3</sub>	0.883	0.910	0.940	0.919 <sup>b</sup>	0.888 <sup>b</sup>	0.887 <sup>b</sup>	0.892 <sup>b</sup>	0.869 <sup>b</sup>	0.846 <sup>b</sup>	0.781 <sup>b</sup>	0.578
+150 µl/l	CF	0.886	0.908	0.941	0.936 <sup>a</sup>	0.941 <sup>a</sup>	0.933 <sup>a</sup>	0.925 <sup>a</sup>	0.903 <sup>a</sup>	0.889 <sup>a</sup>	0.854 <sup>a</sup>	0.601
	CF+O <sub>3</sub>	0.890	0.912	0.941	0.932 <sup>ab</sup>	0.910 <sup>b</sup>	0.899 <sup>b</sup>	0.906 <sup>ab</sup>	0.888 <sup>ab</sup>	0.872 <sup>ab</sup>	0.820 <sup>a</sup>	0.553
LSD	(p<0.05)	0.050	0.035	0.012	0.014	0.027	0.028	0.022	0.023	0.030	0.036	0.105

\* , \*\* significantly different at the 5% and 1% probability level, respectively.

(11%) observed in the final dry biomass (Table 2). Main effects of CO<sub>2</sub> on ND were not significant for any measurement date. However, dry biomass was significantly higher (15%) for the high-CO<sub>2</sub> treated plants (Table 2). The lack of significance for the high-CO<sub>2</sub> treatments in terms of the ND may be attributed to the fact that the canopy reflectance in the near infrared was already close to saturation in the ambient-CO<sub>2</sub> treatments and therefore no significant increase in near infrared waveband could be achieved for the high-CO<sub>2</sub> treatments.

Changes in the fraction of absorbed PAR (FAPAR) as estimated from the ND data using a linear transformation (Eq. 1) are illustrated in Figure 1. Analyses of variance for FAPAR provided the same significance levels observed for ND since both are very closely related.

The absorbed PAR (APAR) was estimated from daily FAPAR and daily incident PAR (Eq. 2) and integrated over the growing season from early vegetative stage to maturation to obtain an estimate of the accumulated APAR. No significant difference was found for the main effect of the CO<sub>2</sub> factor for accumulated APAR, even though significantly higher dry biomass was observed for the enriched CO<sub>2</sub> treatments (Table 2). The O<sub>3</sub> factor significantly reduced the cumulative APAR because less radiation was absorbed by plants grown under high-O<sub>3</sub> (Table 2).

Table 2

Summary of main and simple effects of CO<sub>2</sub> and O<sub>3</sub> treatments on grain yield, dry biomass, harvest index, cumulative APAR and conversion efficiency.

Chamber Treatments		Grain Yield	Dry Biomass	Harvest Index	Cum. APAR	Conv. Effic.
CO <sub>2</sub>	O <sub>3</sub>	(g/m <sup>2</sup> )	(g/m <sup>2</sup> )	(%)	(MJ/m <sup>2</sup> )	(g/MJ)
CO <sub>2</sub> Treatment Means						
Ambient	-	476	1392	34.1	414	3.36
+150 μl/l	-	600	1606	37.4	418	3.82
Statistical significance		**	**	**	ns	**
O <sub>3</sub> Treatment Means						
-	CF	582	1583	36.8	425	3.73
-	CF+O <sub>3</sub>	494	1415	34.7	408	3.45
Statistical significance		**	**	**	**	**
CO <sub>2</sub> and O <sub>3</sub> Treatments						
Ambient	CF	538 <sup>b</sup>	1513 <sup>a</sup>	35.6 <sup>a</sup>	425 <sup>a</sup>	3.54 <sup>b</sup>
	CF+O <sub>3</sub>	414 <sup>c</sup>	1272 <sup>b</sup>	32.5 <sup>b</sup>	403 <sup>b</sup>	3.13 <sup>c</sup>
+150 μl/l	CF	627 <sup>a</sup>	1653 <sup>a</sup>	37.9 <sup>a</sup>	425 <sup>a</sup>	3.91 <sup>a</sup>
	CF+O <sub>3</sub>	574 <sup>ab</sup>	1559 <sup>a</sup>	36.9 <sup>a</sup>	412 <sup>ab</sup>	3.77 <sup>ab</sup>
LSD (p=0.05)		58	156	3.1	15	0.28

\*, \*\* significantly different at the 5 % and 1% probability level, respectively.

Plants grown under enriched CO<sub>2</sub> conditions exhibited a significantly higher conversion efficiency ( $\epsilon$ ) than plants grown under ambient CO<sub>2</sub> (Table 2) even though their accumulated APAR values were not responsive to CO<sub>2</sub>. Significantly lower  $\epsilon$  values were found in response to the high O<sub>3</sub> treatments which were consistent with the reductions in both dry biomass and accumulated APAR. The reduction in  $\epsilon$  in response to O<sub>3</sub> stress may also be attributed to the portion of the PAR<sub>0</sub> striking dead leaf tissue not being converted to dry matter and reduction in photosynthesis in living tissue (Mulchi et al., 1992)

Main effects of CO<sub>2</sub> and O<sub>3</sub> on grain yield (Table 2) were highly significant for both. The high-CO<sub>2</sub> treatments produced 26% more grain than ambient-CO<sub>2</sub> treatments and the high O<sub>3</sub> treatments produced 15% less yield than the low-O<sub>3</sub> treatments. However, in the absence of O<sub>3</sub> stress, plants grown in the enriched CO<sub>2</sub> environment exhibited a 16 % increase in grain yield and plants grown under ambient CO<sub>2</sub> levels and exposed to O<sub>3</sub> showed a 23 % decrease in grain yield. In the presence of the high CO<sub>2</sub> level, exposure to O<sub>3</sub> stress caused a 8 % reduction in grain yield. Therefore, high CO<sub>2</sub> treatment would appear to counteract the negative impact of O<sub>3</sub> stress on wheat as was also observed with soybean (Mulchi et al., 1992). Simple effects of CO<sub>2</sub> produced lower dry biomass and harvest index, but the differences were not significant. Tests for the interactive effect of CO<sub>2</sub> and O<sub>3</sub> were not significant in any of the analysis of variance.



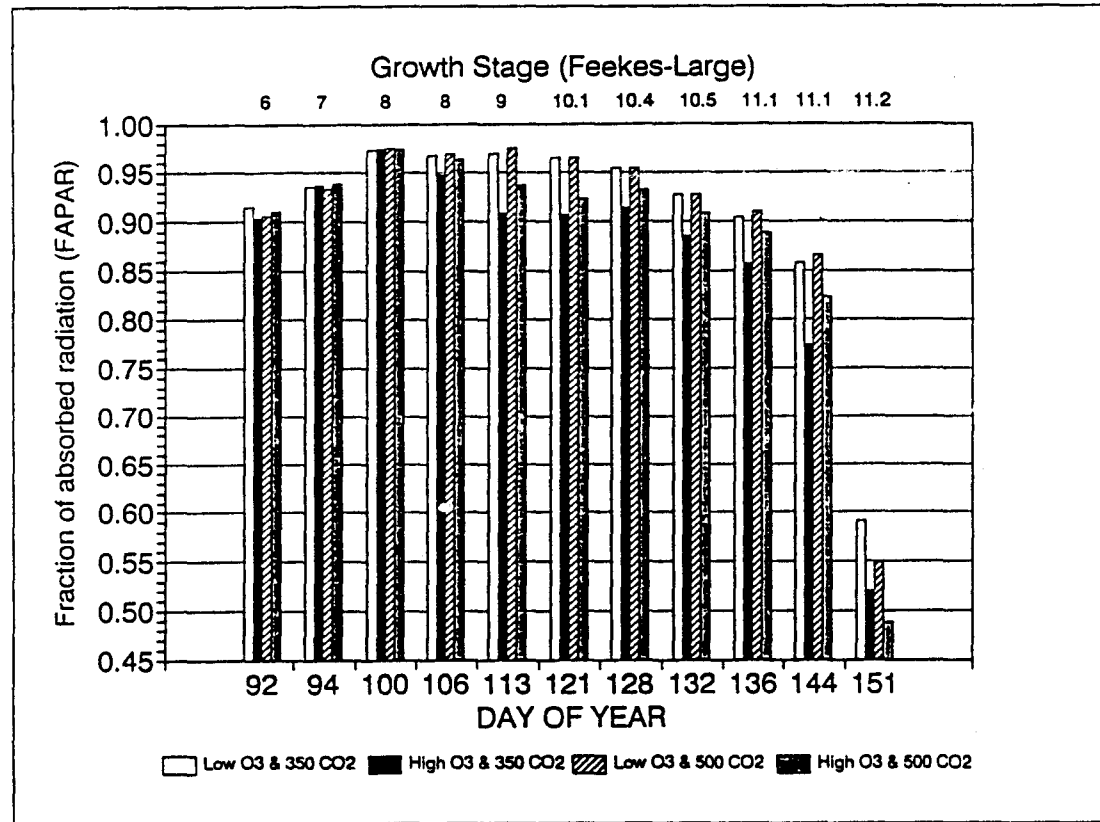


Figure 1 - Simple effects of O<sub>3</sub> and CO<sub>2</sub> on the fraction of absorbed PAR (FAPAR) throughout the winter wheat growing season.

Regression equations were obtained using ND and grain yield data for replicates 1 and 2. These equations were then used to estimate the grain yield for replicates 3 and 4. Representative results from these analysis are presented in Table 3. Due to the relatively high correlation among NDs, regression coefficients seem to be unstable if more than two NDs are used in the equation. Using single ND obtained between stages 10.4 and 11.1, a grain yield variation of 50% to 76% was explained by the ND.

Table 3

Best regression equations for the relationship of grain yield ( $Y_{obs}$ ) vs. normalized difference vegetation index (ND) using replicates 1 and 2 (n=8) and coefficient of determination ( $r^2$ ) for ( $Y_{obs}$ ) for replicates 3 and 4 (n=8) vs. estimated grain yield ( $Y_{est}$ ) from the regression equations.

Growth Stage (Feekes & Large)	Regression Equations	$r^2$	
		$Y_{obs}$ vs. ND	$Y_{obs}$ vs. $Y_{est}$
10.1	$Y_{est} = -977 + 1688ND6$	0.33	0.47
10.4	$Y_{est} = -1688 + 2448ND7$	0.30	0.66
10.5.2	$Y_{est} = -1650 + 2478ND8$	0.32	0.76
11.1	$Y_{est} = -2067 + 2997ND9$	0.56	0.65
11.1	$Y_{est} = -1015 + 1884ND10$	0.77	0.50
8 & 11.1	$Y_{est} = -1351 + 407ND4 + 1834ND10$	0.77	0.54
11.1 & 11.1	$Y_{est} = -1097 + 165ND9 + 1809ND10$	0.77	0.52
8, 10.1 & 11.1	$Y_{est} = -3384 + 4162ND4 - 2406ND6 + 2714ND10$	0.87	0.72
9, 10.4 & 11.1	$Y_{est} = -521 + 245ND5 - 968ND7 + 2079ND10$	0.78	0.46
8, 10.4 & 11.1	$Y_{est} = -2126 + 3305ND4 - 2604ND7 + 2377ND10$	0.83	0.63
8, 10.4, 11.1 & 11.1	$Y_{est} = -2543 + 3670ND4 - 3468ND7 + 1309ND9 + 2037ND10$	0.85	0.70

## CONCLUSIONS

- 1) High-O<sub>3</sub> treatments (79 nl/l) significantly reduced spectral canopy reflectance (ND) after the first visual symptoms of O<sub>3</sub> injury appeared on leaves;
- 2) Accumulated APAR was significantly reduced for the high-O<sub>3</sub> treatments, but no difference was found for the enriched CO<sub>2</sub> treatments;
- 3) High-O<sub>3</sub> and high-CO<sub>2</sub> treatment (79 nl/l O<sub>3</sub> and 500 μl/l CO<sub>2</sub>) showed a trend of lower NDs over the growing season, but higher final dry biomass and grain yield were observed when compared to the control treatment (19 nl/l O<sub>3</sub> and 350 μl/l CO<sub>2</sub>);
- 4) Single ND obtained between heading (stage 10.1) and maturation (stage 11.1) explained from 50% to 76% of the observed grain yield variation.

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