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A Database of Woody Vegetation Responses to Elevated Atmospheric CO₂

Peter S. Curtis

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A DATABASE OF WOODY VEGETATION RESPONSES TO ELEVATED ATMOSPHERIC CO₂

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ABSTRACT

Curtis, P. S., R. M. Cushman, and A. L. Brenkert. 1999. *A Database of Woody Vegetation Responses to Elevated Atmospheric CO₂*. ORNL/CDIAC-120, NDP-072. Carbon Dioxide Information Analysis Center, U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A. 63 pp.

To perform a statistically rigorous meta-analysis of research results on the response by woody vegetation to increased atmospheric CO₂ levels, a multiparameter database of responses was compiled. Eighty-four independent CO₂-enrichment studies, covering 65 species and 35 response parameters, met the necessary criteria for inclusion in the database: reporting mean response, sample size, and variance of the response (either as standard deviation or standard error). Data were retrieved from the published literature and unpublished reports.

This numeric data package contains a 29-field data set of CO₂-exposure experiment responses by woody plants (as both a flat ASCII file and a spreadsheet file), files listing the references to the CO₂-exposure experiments and specific comments relevant to the data in the data set, and this documentation file (which includes SAS®¹ and Fortran codes to read the ASCII data file).

The data files and this documentation are available without charge on a variety of media and via the Internet from the Carbon Dioxide Information Analysis Center (CDIAC).

NDP-072 is an enhancement of previously published CDIAC DB-1018, with additional quality control and documentation (and some corrections to the data, detailed herein).

Keywords: carbon dioxide, meta-analysis, vegetation

¹SAS® is a registered trademark of the SAS Institute, Inc., Cary, North Carolina 27511.

1. BACKGROUND INFORMATION

To perform a statistically rigorous synthesis of research results on the response by vegetation to increased atmospheric CO₂ levels, a multiparameter database of woody-plant responses was compiled (Curtis 1996; Curtis and Wang 1998, included in this report as Appendix D). Eighty-four independent CO₂-enrichment studies, covering 65 species (listed in Appendix A) and 35 response parameters, met the necessary criteria for inclusion in the database: reporting mean response, sample size, and variance of the response (either as standard deviation or standard error). Data were retrieved from the published literature and in a few instances from unpublished reports. Meta-analytical methods (Cooper and Hedges 1994; Gurevitch and Hedges 1993; Gurevitch et al. 1992) have been applied to part of this database (Curtis 1996; Curtis and Wang 1998).

Physiological "acclimation" or "downward regulation" of photosynthetic rates, stomatal conductance, dark respiration, and water-use efficiency of plants exposed to elevated CO₂ levels can be analyzed, keeping the following definitions in mind. "Acclimation" is in general defined as "diminishing enhancement of photosynthesis by elevated CO₂ with time" (Mousseau and Saugier 1992). "Downward regulation" can be defined as "the initial stimulation of enhanced photosynthesis and growth by atmospheric enrichment eroding with time" (Idso and Kimball 1992). The phenomenon is also called "downward acclimation" (Curtis and Teeri 1992): "following prolonged exposure to high CO₂, photosynthetic capacity measured at either elevated or ambient CO₂ partial pressure falls to below that of plants exposed only to ambient CO₂." When more than one elevated CO₂ treatment level was reported, only the elevated CO₂ level that was approximately twice the ambient level was included in the database. Only the longest lasting exposure experiment results on photosynthetic rates, stomatal conductance, dark respiration and water use efficiency are included, however, not multiple measurements over time from the same plant. And only responses of plants measured at elevated levels of CO₂ are included for evaluation of acclimatory responses. Durations of experimental exposures are always reported.

2. APPLICATIONS OF THE DATA

This database was produced to support a meta-analysis of the effects of elevated CO₂ on woody vegetation (Curtis 1996; Curtis and Wang 1998), and it was formatted accordingly. For other applications, the user should be aware that the data may be reported in more than one unit for a given variable (e.g., for dark respiration, the data are reported in units of mg/g/d, mmol/g/h, mmol/m²/h, μ mol/g/s, and μ mol/m²/s; and the experimental CO₂ concentrations are reported in units of cm³/m³, Pa, ppm, μ bar, μ l/l, and μ mol/mol); this is not a problem for meta-analysis, but for other applications the user may need to convert the data to consistent units.

The effects of environmental factors (e.g., nutrient levels, light intensity, temperature), stress treatments (e.g., drought, heat, ozone, ultraviolet-B radiation), and the effects of experimental conditions (e.g., duration of CO₂ exposure, pot size, type of CO₂ exposure facility) on plant responses to elevated CO₂ levels can be explored with this database.

3. DATA LIMITATIONS AND RESTRICTIONS

In many papers, the data were reported graphically, rather than numerically. In such cases, the data values reported herein were digitized from the printed figures and may therefore be less accurate.

There might also have been some confusion because of the term "standard deviation." When a "standard deviation" was reported in a published paper, it was not generally possible to verify whether this value was a *sample* standard deviation or the standard deviation *of the mean*, which is sometimes used synonymously with standard error (i.e., standard error of the mean). Unfortunately, it was not possible to settle this issue definitively without personally contacting the authors of the published papers. In all cases, where not specified or known to be otherwise, a reported standard deviation was taken to be the sample standard deviation. If this was in error, then the standard deviation, standard error, and coefficient of variation reported in this database would all be incorrect.

In some cases an error bar in a figure or confidence interval in a table was not specified as standard deviation or standard error, in which case the data contributors had to make an assumption from the error bar or confidence interval and the sample size. Instances where data were obtained by personal communication with the authors, or where standard deviation or standard error was inferred from the published data, are documented in the comments.* files (included as Appendix C). Where it was not possible to determine whether the reported variability was standard deviation or standard error, it was assumed to be standard error, for the sake of conservatism.

In some cases (e.g., in long-term exposures), duration of the CO₂ exposure was approximated.

As noted in Sect. 2, various units may be used for the same parameter, so the user should apply caution in integrating observations from more than one paper. The units are reported in this database.

4. DATA CHECKS AND PROCESSING PERFORMED BY CDIAC

An important part of the data packaging process at CDIAC involves the quality assurance (QA) of data before distribution. To guarantee data of the highest possible quality, CDIAC performs

extensive QA checks, examining the data for completeness, reasonableness, and accuracy, through close cooperation with the data contributor.

This database was originally published as CDIAC DB-1018, for which all entries in the data file were visually inspected for reasonableness and selected entries were spot-checked against the original publications. Additional quality-assurance and documentation was performed in the preparation of this numeric data package, and some data were corrected, as described herein.

The following describes the additional data checks that were performed in the preparation of this numeric data package and the resulting revisions to the database.

Using Excel, the spreadsheet included in the original database (db1018.xls) was converted to Lotus 1-2-3 format (ndp072.wk1). Headings were added to all columns.

Lists of entries for each field were generated, to identify possible spelling variants, typographical errors, or order-of-magnitude errors in the original literature or in the compilation and data entry of the database. In fact, some variant spellings of **GENUS**, **SPECIES**, and **P_UNIT** were identified and corrected for the sake of consistency.

The definition of parameter LFTNC was corrected, from "leaf N (TNC free weight basis)" to "leaf total nonstructural carbohydrate."

The internal consistency of the reported standard errors (s.e.), standard deviations (s.d.), and sample sizes (n) was checked by calculating s.d. from the s.e. and n in DB-1018 and comparing the resulting values of s.d. with the values in DB-1018; discrepancies were resolved by checking the original publications.

The ratio of elev/amb for X, SE, SD, and N was calculated; then all observations were ranked on the basis of each ratio to identify suspect values.

The following lists the changes that were made to the original database.

SOURCE: In entire spreadsheet, edited format of letters following T or F number to entirely lowercase.

OBS 39 & 40 (PAP_NO 150): Corrected **P_UNIT**, from molH₂O/m²/s to mmolH₂O/m²/s.

OBS 142 (PAP_NO 340): Replaced existing value of **SD_AMB** (0.9798) with value calculated from **SE_AMB** & **N_AMB** (2.4495).

OBS 143 & 151 (PAP_NO 340): Corrected **P_UNIT**, from 0.01g/m² to 10² g/g.

OBS 150 (PAP_NO 340): Replaced existing value of **SD_AMB** (3.9192) with value calculated from **SE_AMB** & **N_AMB** (1.9596).

OBS 191 (PAP_NO 505): Corrected **SOURCE**, from F2b to F2c.

OBS 191 (PAP_NO 505): Replaced existing values of **SD_AMB** (5.134) and **SD_ELEV** (7.7972) with values calculated from **SE** & **N** (**SD_AMB** = 10.268 and **SD_ELEV** = 3.487).

OBS 192 (PAP_NO 505): Replaced existing values of **SD_AMB** (5.367), **SD_ELEV** (5.747), **SE_AMB** (2.4), **SE_ELEV** (2.57), **N_AMB** (20), and **N_ELEV** (20) with values provided by author: **SD_AMB** (5.484), **SD_ELEV** (4.406), **SE_AMB** (2.452), **SE_ELEV** (1.970), **N_AMB** (5), and **N_ELEV** (5).

OBS 195 (PAP_NO 505): Corrected **P_UNIT**, from mgdvvt/cm³ to mgdwt/cm³.

OBS 210 & 211 (PAP_NO 506): Corrected **P_UNIT**, from umol/H₂O/m²/s to mol/H₂O/m²/s.

OBS 364 & 365 (PAP_NO 746): Corrected **SPECIES** name from tulipfera to tulipifera.

OBS 598-599, 606-607, and 612-613 (PAP_NO 2110): Existing values for means, standard error, and standard deviation multiplied by 100, based on personal communication from author, to correct for error in the published paper (in converting from % to mg/g, data were divided by 10 rather than multiplied by 10). Personal correspondence with author also confirmed that variance values given parenthetically in Table 2 were standard deviations; the tabulated data were corrected accordingly.

To search for possible confusion between standard error and standard deviation (see Sect. 3, **DATA LIMITATIONS AND RESTRICTIONS**), coefficients of variation **CV*** (after Sokal and Rohlf 1981) were calculated for each **PARAM** from each mean, standard deviation, and sample size. It was expected that, for any **PARAM**, an anomalously low coefficient of variation for a given observation might signal that a standard error was mislabeled as a standard deviation; but no such anomalies were obvious. The database was sorted by **PARAM**, then by **CV*_AMB** and **CV*_ELEV**, and inspected for jumps of greater than fourfold between adjacent observations. The following lists those adjacent observations that warranted further scrutiny, along with the results of the checks:

PARAM = BD

OBS 396, PAP_NO 2004 (CV*_AMB = 35.5828): Contacted author and verified that "mean ± SD" actually referred to sample standard deviation rather than standard error of the mean.

OBS 758, PAP_NO 2224 (CV*_AMB = 623.5): Verified tabulated value against publication.

PARAM = BGWT

OBS 380, PAP_NO 2003 (CV*_AMB=0) and OBS 378, PAP_NO 2003 (CV*_AMB=2.3864): Verified tabulated values against publication.

PARAM = LFC

OBS 599, PAP_NO 2110 (CV*_AMB=3.2753): Personal correspondence with author confirmed that variance values given parenthetically in Table 2 were standard deviations; the tabulated data were corrected accordingly.

OBS 490, PAP_NO 2043 (CV*_AMB=16.6223): Verified tabulated value against publication.

PARAM = LFNM

OBS 414, PAP_NO 2027 (CV*_AMB=0.4532) and OBS 251, PAP_NO 550 (CV*_AMB=2.3447): Verified tabulated values against publication.

PARAM = PN

OBS 513, PAP_NO 2045 (CV*_AMB=-99.0208): Verified tabulated value against publication.

OBS 638, PAP_NO 2120 (CV*_AMB=2.6460): Based on personal communication; did not verify.

PARAM = PN_AC

OBS 520, PAP_NO 2045 (CV*_AMB=-99.0208) and OBS 622, PAP_NO 2117 (CV*_AMB=4.6109): Verified tabulated values against publication.

PARAM = RD_AC

OBS 589, PAP_NO 2068 (CV*_AMB=96.7737) and OBS 162, PAP_NO 468 (CV*_AMB=1073.9583): Verified tabulated values against publication.

PARAM = INDLA

OBS 18, PAP_NO 44 (CV*_ELEV=10.1423) and OBS 17, PAP_NO 44 (CV*_ELEV=43.9153): Verified tabulated values against publication.

PARAM = LFC

OBS 599, PAP_NO 2110 (CV*_ELEV=1.9585): Personal correspondence with author confirmed that variance values given parenthetically in Table 2 were standard deviations; the tabulated data were corrected accordingly.

OBS 490, PAP_NO 2043 (CV*_ELEV=13.8699): Corrected **PARAM** to LFTNC.

PARAM = LFSTAR

OBS 151, PAP_NO 340 (CV*_ELEV=39.3519) and OBS 143, PAP_NO 340 (CV*_ELEV=554.3478): Verified tabulated values against publication.

PARAM = LFTNC

OBS 416, PAP_NO 2027 (CV*_ELEV=1.2777) and OBS 773, PAP_NO 2224 (CV*_ELEV=7.7891): Verified tabulated values against publication.

PARAM = RD_AC

OBS 589, PAP_NO 2068 (CV*_ELEV=11.2191) and OBS 588, PAP_NO 2068 (CV*_ELEV=129.3295): Verified tabulated values against publication.

PARAM = RGR

OBS 759, PAP_NO 2224 (CV*_ELEV=10.8333): Verified tabulated value against publication.

OBS 406 & 407, PAP_NO 2026 (CV*_ELEV=78.1250): The value for X_ELEV was corrected, from 0.0052 to 0.052, thereby lowering the calculated CV*_ELEV to a less anomalous 7.8125.

OBS 192, PAP_NO 505 (CV*_ELEV=105.7878): Tabulated data changed, as described earlier in this section, based on personal communication from author.

PARAM = TOTN

OBS 613, PAP_NO 2110 (CV*_ELEV=39.0833) - Personal correspondence with author confirmed that variance values given parenthetically in Table 2 were standard deviations; the tabulated data were corrected accordingly.

OBS 243, PAP_NO 521 (CV*_ELEV=177.7945) - Error bar not labeled as to SD or SE. Assumed by data contributor to be SE, based on size of the error bars and the sample size.

5. INSTRUCTIONS FOR OBTAINING THE DATA AND DOCUMENTATION

This database (NDP-072) is available free of charge from CDIAC. The files are available via the Internet, from CDIAC's World-Wide-Web site (<http://cdiac.esd.ornl.gov>), or from CDIAC's anonymous FTP (file transfer protocol) area (cdiac.esd.ornl.gov) as follows:

- FTP to cdiac.esd.ornl.gov (128.219.24.36).
- Enter "ftp" as the user id.
- Enter your electronic mail address as the password (e.g., fred@zulu.org).
- Change to the directory "pub/ndp072" (i.e., use the command "cd pub/ndp072").
- Set ftp to get ASCII files by using the ftp "ascii" command.
- Retrieve the ASCII database documentation file by using the ftp "get ndp072.txt" command.
- Retrieve the ASCII data files by using the ftp "mget *.dat" command.
- Set ftp to get binary files by using the ftp "binary" command.
- Retrieve the binary spreadsheet files by using the ftp "mget *.wk1" command.
- Exit the system by using the ftp "quit" command.

Uncompress files on computer, if obtained in compressed format.

For **non-Internet data acquisitions** (e.g., floppy diskette or 8-mm tape), or for additional information, contact:

User Services
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E-mail: cdiac@ornl.gov

Note: After 1 November 1999, the area code 423 will be changed to 865.

6. REFERENCES

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Strain, B. R., and J. D. Cure. 1994. *Direct effects of atmospheric CO₂ enrichment on plants and ecosystems: An updated bibliographic database*. ORNL/CDIAC-70. Carbon Dioxide Information Analysis Center, U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

7. LISTING OF FILES PROVIDED

The database consists of seven files (see Table 1), including this documentation file. The data file (ndp072.dat and ndp072.wk1), reference file (refs.dat and refs.wk1), and comment file (comments.dat and comments.wk1) are each formatted in two ways: as flat ASCII files and as binary spreadsheet files (in Lotus² 1-2-3 format, but readable by other spreadsheet programs).

The 29-field ndp072.dat and ndp072.wk1 files contain data (784 observations in all) relevant for CO₂-exposure meta-analysis for woody plants. The ndp072.dat file can be read into SAS® or Fortran programs, using the access codes provided in Sect. 11 of this numeric data package. The ndp072.dat file can also be converted into a spreadsheet file for processing, although it is simpler to use the ndp072.wk1 spreadsheet file provided in this numeric data package.

The refs.* files list the selected literature represented in the data files (84 references in all), and the comments.* files provide additional information about the studies, beyond what appears in the ndp072.* data files. The reference numbers in the refs.* and comments.* correspond to the paper numbers in the ndp072.* data files.

²Lotus 1-2-3 is a registered trademark of the Lotus Development Corporation, Cambridge, Massachusetts 02142

Table 1. Data files in the database

File number	File name	File size (kB)	File type	File description
1	ndp072.txt	81	ASCII text	Documentation file
2	ndp072.dat	185	ASCII text	Data file
3	ndp072.wk1	392	Binary spreadsheet	Data file
4	refs.dat	18	ASCII text	Reference file
5	refs.wk1	21	Binary spreadsheet	Reference file
6	comments.dat	24	ASCII text	Comment file
7	comments.wk1	25	Binary spreadsheet	Comment file

8. DESCRIPTION OF THE DOCUMENTATION FILE

ndp072.txt (File 1)

This file is an ASCII text equivalent to this document.

9. DESCRIPTION, FORMAT, AND PARTIAL LISTINGS OF THE ASCII DATA FILES

ndp072.dat (File 2)

Table 2 describes the format and contents of the ASCII data file **ndp072.dat** distributed with this numeric data package. This table also indicates the column in the corresponding spreadsheet file **ndp072.wk1** in which each variable is found.

Table 2. Contents and format of ndp072.dat (File 2)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Spreadsheet column	Definition and comments
OBSNO	Numeric	3	1	3		A	Observation number
PAP_NO	Numeric	4	4	7	See below	B	Cited paper numbers
PARAM	Character	6	8	13	See below	C	Measured parameter
P_UNIT	Character	15	14	28		D	Unit for PARAM
GENUS	Character	13	29	41		E	Plant genus name
SPECIES	Character	25	42	66		F	Plant species name
DIV1	Character	5	67	71	See below	G	Functional division #1
DIV2	Character	5	72	76	See below	H	Functional division #2
AMB	Character	4	77	80	See CO2_UNIT	I	Ambient CO ₂ treatment level
ELEV	Character	4	81	84	See CO2_UNIT	J	Elevated CO ₂ treatment level
CO2_UNIT	Character	8	85	92	See below	K	Units for CO ₂ exposure concentration
TIME	Numeric	4	93	96	Days	L	Maximum duration of CO ₂ exposure
POT	Character	6	97	102	See below	M	Growing method
METHOD	Character	4	103	106	See below	N	CO ₂ -exposure facility
STOCK	Character	8	107	114	See below	O	Planting stock
XTRT	Character	6	115	120	See below	P	Interacting treatment
LEVEL	Character	7	121	127	See below	Q	Interacting treatment level

Table 2 (continued)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Spreadsheet column	Definition and comments
QUANT	Character	24	128	151	See below	R	Quantity and unit associated with LEVEL
SOURCE	Character	6	152	157	See below	S	Figure, table, or page from which data were taken
X_AMB	Numeric	10	158	167	See P_UNIT	T	Mean response of plants grown in ambient CO ₂
SE_AMB	Numeric	9	168	176	See P_UNIT	U	Standard error of X_AMB
SD_AMB	Numeric	10	177	186	See P_UNIT	V	Standard deviation of responses of plants grown in ambient CO ₂
CV*_AMB	Numeric	9	187	195	%	W	Coefficient of variation of responses of plants grown in ambient CO ₂
N_AMB	Numeric	3	196	198		X	Sample size of responses of plants grown in ambient CO ₂
X_ELEV	Numeric	10	199	208	See P_UNIT	Y	Mean response of plants grown in elevated CO ₂
SE_ELEV	Numeric	9	209	217	See P_UNIT	Z	Standard error of X_ELEV
SD_ELEV	Numeric	10	218	227	See P_UNIT	AA	Standard deviation of responses of plants grown in elevated CO ₂

Table 2 (continued)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Spreadsheet column	Definition and comments
CV*_ELEV	Numeric	9	228	236	%	AB	Coefficient of variation of responses of plants grown in elevated CO ₂
N_ELEV	Numeric	3	237	239		AC	Sample size of responses of plants grown in elevated CO ₂

Where:

For **PAP_NO**, a value < 2000 indicates abstracts in Strain and Cure (1994), and a value >2000 indicates more recent literature.

For **PARAM**, the following define the possible measured parameters:

plant parts

AGWT: total aboveground weight
 BD: basal diameter
 BGWT: total belowground weight
 CRWT: coarse root weight
 FRWT: fine root weight
 HT: height
 LFWT: total leaf weight
 RGR: relative growth rate
 SEEDWT: reproductive biomass
 STWT: stem weight
 TOTWT: whole plant weight

leaf area components

INDLA: maximum individual leaf area
 LAR: leaf area ratio (leaf area/unit mass of plant)
 MAXLA: maximum canopy leaf area
 SLA: specific leaf area (leaf area/unit mass of leaf)
 SLW: specific leaf weight (leaf mass/unit area of leaf)

gas-exchange parameters

GS: stomatal conductance of ambient plants measured under ambient CO₂ (X_AMB) and elevated plants measured under elevated CO₂ levels (X_ELEV)
 GS_AC: stomatal conductance of ambient plants measured at elevated CO₂ (X_AMB) and elevated plants measured at elevated CO₂ levels (X_ELEV)
 JMAX: maximum rate of electron transport
 PIRC: rate of phosphate regeneration
 PN: net CO₂ assimilation of ambient plants measured under ambient CO₂ (X_AMB) and elevated plants measured under elevated CO₂ levels (X_ELEV)
 PN_AC: net CO₂ assimilation of ambient plants measured at elevated CO₂ (X_AMB) and elevated plants measured at elevated CO₂ levels (X_ELEV)
 RD: dark respiration of ambient plants measured under ambient CO₂ (X_AMB) and elevated plants measured under elevated CO₂ levels (X_ELEV)
 RD_AC: dark respiration of ambient plants measured at elevated CO₂ (X_AMB) and elevated plants measured at elevated CO₂ levels (X_ELEV)
 VCMAX: maximum carboxylation rate of Rubisco
 WUE: water use efficiency of ambient plants measured under ambient CO₂ (X_AMB) and elevated plants measured under elevated CO₂ levels (X_ELEV)
 WUE_AC: water use efficiency of ambient plants measured at elevated CO₂ (X_AMB) and elevated plants measured at elevated CO₂ levels (X_ELEV)

biochemical constituents

LFC: leaf total C (unit mass basis)
 LFNA: leaf N (unit area basis)
 LFNM: leaf N (unit mass basis)
 LFTNC: leaf total non-structural carbohydrate
 LFP: leaf P (unit mass basis)
 LFSTAR: leaf starch (unit mass basis)
 LFSUG: leaf sugar (unit mass basis)
 TOTN: total N (concentration)

The value of **PARAM** is linked to that shown for **P_UNIT** (parameter units), **X_AMB** (parameter value for plants grown under ambient CO₂ exposure conditions), and **X_ELEV** (parameter value for plants grown under elevated CO₂ exposure conditions).

All entries for **DIV1** are "WOODY" in this database.

Entries for **DIV2** are:

ANGIO: angiosperms
 GYMNO: gymnosperms
 N2FIX: nitrogen fixation by species in experiment

The values of **AMB** and **ELEV** are linked to that shown for **CO2_UNIT**.

Entries for **CO2_UNIT** are:

Pa (Pascals)

μbar ($1 \mu\text{bar} = 0.1 \text{ Pa}$)

ppm

$\mu\text{L/l}$

cm^3/m^3

$\mu\text{mol/mol}$

For **POT**, a numeric entry signifies pot size (in liters) used during the major part of the experiment; the other entries are:

GRND: plants rooted in the ground

HYDRO: solution or aeroponic culture

Entries for **METHOD** are:

BRANCH: branch chambers

GC: indoor, controlled environment: growth chambers

GH: sunlit greenhouses and chambers within greenhouses

OTC: field-based open-top chambers

SPAR: high-tech soil-plant-atmosphere chambers

Entries for **STOCK** are:

BRANCH: branches exposed

MATURE: mature plants exposed

SAP: plants started from cuttings

SEED: plants started from seeds

Entries for **XTRT** are:

NONE: no treatment

COMP: plant competition

FERT+L: soil fertility and light

FERT: soil fertility

H2O: well-watered vs drought

LIGHT: light treatment

TEMP: temperature treatment

OZONE: ozone exposure

UVB: ultraviolet-B radiation exposure

The entries for **LEVEL** (which qualitatively describes the treatment level) are treatment-dependent and cannot be further categorized; this field is linked with **XTRT** (which characterizes the treatment type) and **QUANT** (which quantifies the treatment level).

For **XTRT** = NONE, COMP, or FERT+L, **LEVEL** = . (missing value) (see entry for corresponding paper in **comments.*** file)

For soil fertility treatment:

FERT - HI

LOW

CONTROL

missing (.) when treatment can not be clearly described (see entry for corresponding paper in **comments.*** file).

For H2O treatment:

DRT: drought

WW: well-watered

For LIGHT treatment:

HI

LOW

For TEMP treatment:

HI

LOW

CONTROL

For stress interactions:

OZONE

HI

LOW

UVB

HI

LOW

Entries for **QUANT**, which quantify the interacting treatment level, are treatment-dependent. The combination of quantity and unit is reported in this one field (see also the corresponding entry in **comments.*** file). The missing-value indicator for **QUANT** is a period (.).

Possible entry formats for **SOURCE** are:

F1a (Fig. 1a)

T1 (Table 1)

P235 (Page 235 of text)

1emeta (personal communication with authors)

Entries for **X_AMB**, **SE_AMB**, **SD_AMB**, **X_ELEV**, **SE_ELEV**, and **SD_ELEV** are linked to the units given for **P_UNIT**. The suffix "**AMB**" refers to measurements of plants grown under ambient CO₂ exposure conditions, and the suffix "**ELEV**" refers to measurements of plants grown under elevated CO₂ exposure conditions.

For CV*_AMB and CV*_ELEV, corrected (for small sample size) coefficient of variation was calculated according to Sokal and Rohlf (1981) as follows:

$$CV^* = (1 + 1/4N)(SD \times 100)/X$$

where SD = standard deviation, X = mean, and N = sample size.

First two data records:

1	44PN	umolCO2/m2/s	ALNUS	RUBRA			
WOODYN2FIX	350	650ul/l	46	0.5GC	SEED	FERT	HI
20mgN/l			T3	11.7700	0.6400		1.4311
12.7668	5	23.2000	4.6100	10.3083	46.6539	5	
2	44PN	umolCO2/m2/s	ALNUS	RUBRA			
WOODYN2FIX	350	650ul/l	46	0.5GC	SEED	FERT	CONTROL.
			T3	11.7000	1.1600	2.5938	23.2777
25.9000	1.4800	3.3094	13.4165	5			

Last two data records:

7832224TOTWT	g		POPULUS	TREMULOIDES			
WOODYANGIO	385	642ul/l	60	6GC	SEED	NONE	.
		F1	69.7000	2.1000	3.6373		5.6534
102.6000	3.6000	6.2354	6.5838	3			
7842224LFSTAR%			POPULUS	TREMULOIDES			
WOODYANGIO	385	642ul/l	60	6GC	SEED	NONE	.
		F2	2.7600	0.1900	0.3291		12.9176
8.5300	0.9300	1.6108	20.4576	3			

refs.dat (File 4)

This ASCII file provides citations of papers included in the database. A full listing of the file is included as **APPENDIX B**.

comments.dat (File 6)

This ASCII file provides experimental details from papers included in the database. A full listing of the file is included as **APPENDIX C**.

10. DESCRIPTION AND FORMAT OF THE LOTUS 1-2-3 BINARY SPREADSHEET FILES

Three Lotus 1-2-3 binary spreadsheet files (files 3, 5, and 7) contain the same information as the corresponding *.dat ASCII files 2, 4, and 6.

ndp072.wk1 (File 3)

This Lotus 1-2-3 binary spreadsheet file corresponds to ASCII file **ndp072.dat (File 2)**. Table 2, which describes the contents and format of **ndp072.dat**, also indicates the column of **ndp072.wk1** in which each variable is found.

refs.wk1 (File 5)

This Lotus 1-2-3 binary spreadsheet file corresponds to ASCII file **refs.dat (File 4)**.

comments.wk1 (File 7)

This Lotus 1-2-3 binary spreadsheet file corresponds to ASCII file **comments.dat (File 6)**.

11. SAS® AND FORTRAN CODES TO ACCESS THE DATA

The following is SAS® code to read file **ndp072.dat**

```
*SAS data retrieval routine to read ndp072.dat;

data ndp072;
infile 'ndp072.dat';
input OBSNO 1-3 @4 PAP_NO 4. @8 PARAM $char6. P_UNIT $ 14-28 GENUS $ 29-41
      SPECIES $ 42-66 DIV1 $ 67-71 DIV2 $ 72-76 AMB $ 77-80 ELEV $ 81-84
      CO2_UNIT $ 85-92 TIME 93-96 POT $ 97-102 METHOD $ 103-106
      STOCK $ 107-114 XTRT $ 115-120 LEVEL $ 121-127 QUANT $ 128-151
      SOURCE $ 152-157 X_AMB 158-167 SE_AMB 168-176 SD_AMB 177-186
      CV_AMB 187-195 N_AMB 196-198 X_ELEV 199-208 SE_ELEV 209-217
      SD_ELEV 218-227 CV_ELEV 228-236 N_ELEV 237-239 ;

* In the above INPUT statement, the variables CV*_AMB and CV*_ELEV have
  been renamed CV_AMB and CV_ELEV, respectively.;

run;
```

The following is Fortran code to read file **ndp072.dat**

```
C *** Fortran program to read the file "ndp072.dat"
C
      INTEGER OBSNO, PAP_NO, N_AMB, N_ELEV, TIME
      DOUBLE PRECISION X_ELEV, SD_ELEV
      REAL X_AMB, SE_AMB, SD_AMB, CV_AMB, SE_ELEV, CV_ELEV
```

```

      CHARACTER PARAM*6, P_UNIT*15, GENUS*13, SPECIES*25, DIV1*5,
+ DIV2*5, AMB*4, ELEV*4, CO2_UNIT*8, POT*6, METHOD*4, STOCK*8,
+ XTRT*6, LEVEL*7, QUANT*24, SOURCE*6
C
      OPEN (UNIT=1, FILE='NDP072.DAT')
C
      Note that the variables CV*_AMB and CV*_ELEV have
C      been renamed CV_AMB and CV_ELEV, respectively
C
10 READ (1,100,END=99) OBSNO, PAP_NO, PARAM, P_UNIT, GENUS, SPECIES,
+ DIV1, DIV2, AMB, ELEV, CO2_UNIT, TIME, POT, METHOD, STOCK, XTRT,
+ LEVEL, QUANT, SOURCE, X_AMB, SE_AMB, SD_AMB, CV_AMB, N_AMB, X_ELEV,
+ SE_ELEV, SD_ELEV, CV_ELEV, N_ELEV
100 FORMAT (I3,I4,A6,A15,A13,A25,2A5,2A4,A8,A4,A6,A4,A8,A6,A7,A24,
+ A6,F9.4,1X,F8.4,1X,2(F9.4,1X),I2,3(F9.4,1X),F8.4,1X,I2)
C
      GO TO 10
99 CLOSE (UNIT=1)
      STOP
      END

```

APPENDIX A: SPECIES INCLUDED IN DATABASE

<i>Acacia mangium</i>	<i>Pinus echinata</i>
<i>Acer pensylvanicum</i>	<i>Pinus eldarica</i>
<i>Acer pseudoplatanus</i>	<i>Pinus nigra</i>
<i>Acer rubrum</i>	<i>Pinus ponderosa</i>
<i>Acer saccharinum</i>	<i>Pinus radiata</i>
<i>Acer saccharum</i>	<i>Pinus strobus</i>
<i>Alnus glutinosa</i>	<i>Pinus sylvestris</i>
<i>Alnus rubra</i>	<i>Pinus taeda</i>
<i>Betula alleghaniensis</i>	<i>Piper auritum</i>
<i>Betula lenta</i>	<i>Poncirus trifoliata</i> x <i>citrusparadisi</i>
<i>Betula papyrifera</i>	<i>Poncirus trifoliata</i> x <i>citruissinensis</i>
<i>Betula pendula</i>	<i>Populus euramericana</i>
<i>Betula populifolia</i>	<i>Populus grandidentata</i>
<i>Betula pubescens</i>	<i>Populus interamericana</i>
<i>Brachychiton populneum</i>	<i>Populus tremuloides</i>
<i>Castanea sativa</i>	<i>Populus</i> x <i>euramericana</i>
<i>Cecropia obtusifolia</i>	<i>Pseudotsuga menziesii</i>
<i>Cedrus atlantica</i>	<i>Quercus alba</i>
<i>Citrus aurantium</i>	<i>Quercus prinus</i>
<i>Citrus sinensis</i>	<i>Quercus robur</i>
<i>Eucalyptus microtheca</i>	<i>Quercus rubra</i>
<i>Eucalyptus polyanthemus</i>	<i>Senna multijuga</i>
<i>Eucalyptus tetrodonta</i>	<i>Tabebuia rosea</i>
<i>Fagus grandifolia</i>	<i>Trichospermum mexicanum</i>
<i>Fagus sylvatica</i>	
<i>Ficus obtusifolia</i>	
<i>Fraxinus americana</i>	
<i>Garcinia mangostana</i>	
<i>Gliricidia sepium</i>	
<i>Lindera Benzoin</i>	
<i>Liquidambar styraciflua</i>	
<i>Liriodendron tulipifera</i>	
<i>Malus domestica</i>	
<i>Maranthes corymbosa</i>	
<i>Myriocarpa longipes</i>	
<i>Nothofagus fusca</i>	
<i>Picea abies</i>	
<i>Picea glauca</i>	
<i>Picea mariana</i>	
<i>Pinus banksiana</i>	

APPENDIX B: FULL LISTING OF REFS.DAT (FILE 4)

The number at the beginning of each entry corresponds to **PAP_NO**, the cited paper number, as defined in Sect. 9.

44 Arnone, J.A., III, and J.C. Gordon. 1990. Effect of Nodulation, Nitrogen Fixation and CO₂ Enrichment on the Physiology, Growth and Dry Mass Allocation of Seedlings of *Alnus rubra* Bong. *New Phytologist* 116:55-66.

2186 Bassow, S.L., K.D.M. McConnaughay, and F.A. Bazzaz. 1994. The Response of Temperate Tree Seedlings Grown in Elevated CO₂ to Extreme Temperature Events. *Ecological Applications* 4(3):593-603.

2223 Bazzaz, F.A., and S.L. Miao. 1993. Successional Status, Seed Size, and Responses of Tree Seedlings to CO₂, Light and Nutrients. *Ecology* 74(1):104-112.

2037 Bazzaz, F.A., S.L. Miao, and P.M. Wayne. 1993. CO₂-induced Growth Enhancements of Co-occurring Tree Species Decline at Different Rates. *Oecologia* 96:478-482.

2217 Berryman, C.A., D. Eamus, and G.A. Duff. 1993. The Influence of CO₂ Enrichment on Growth, Nutrient Content and Biomass Allocation of *Maranthos corymbosa*. *Australian Journal of Botany* 41:195-209.

112 Brown, K.R. 1991. Carbon Dioxide Enrichment Accelerates the Decline in Nutrient Status and Relative Growth Rate of *Populus tremuloides* Michx. Seedlings. *Tree Physiology* 8:161-173.

121 Bunce, J.A. 1992. Stomatal Conductance, Photosynthesis and Respiration of Temperate Deciduous Tree Seedlings Grown Outdoors at an Elevated Concentration of Carbon Dioxide. *Plant, Cell and Environment* 15:541-549.

2026 Callaway, R.M., E.H. DeLucia, E.M. Thomas, and W.H. Schlesinger. 1994. Compensatory Responses of CO₂ Exchange and Biomass Allocation and their Effects on the Relative Growth Rate of *Ponderosa* Pine in Different CO₂ and Temperature Regimes. *Oecologia* 98:159-166.

2043 Cipollini, M.L., B.G. Drake, and D. Whigham. 1993. Effects of Elevated CO₂ on Growth and Carbon/Nutrient Balance in the Deciduous Woody Shrub *Lindera Benzoin* (L.) Blume (Lauraceae). *Oecologia* 96:339-346.

150 Conroy, J.P., M. Kupperts, B. Kupperts, J. Virgona, and E.W.R. Barlow. 1988. The Influence of CO₂ Enrichment, Phosphorus Deficiency and Water Stress on the Growth, Conductance and Water Use of *Pinus radiata* D. Don. *Plant, Cell and Environment* 11:91-98.

159 Couteaux, M.M., P. Bottner, H. Rouhier, and G. Billes. 1992. Atmospheric CO₂ Increase and Plant Material Quality: Production, Nitrogen Allocation and Litter Decomposition of Sweet Chestnut. IN: Responses of Forest Ecosystems to Environmental Changes (A. Teller, P. Mathy, and J.N.R. Jeffers, eds.), Elsevier Applied Science, London, pp. 429-436.

- 168 Curtis, P.S., and J.A. Teeri. 1992. Seasonal Responses of Leaf Gas Exchange to Elevated Carbon Dioxide in *Populus grandidentata*. *Canadian Journal of Forest Research* 22:1320-1325.
- 2039 Curtis, P.S., C.S. Vogel, K.S. Pregitzer, D.R. Zak, and J.A. Teeri. 1995. Interacting Effects of Soil Fertility and Atmospheric CO₂ on Leaf Area Growth and Carbon Gain Physiology in *Populus x euramericana* (Dode) Guinier. *New Phytologist* 129:253-263.
- 2129 Curtis, P.S., D.R. Zak, K.S. Pregitzer, and J.A. Teeri. 1994. Above- and Belowground Response of *Populus grandidentata* to Elevated Atmospheric CO₂ and Soil N Availability. *Plant and Soil* 165:45-51.
- 184 Downton, W.J.S., W.J.R. Grant, and E.K. Chacko. 1990. Effect of Elevated Carbon Dioxide on the Photosynthesis and Early growth of Mangosteen (*Garcinia mangostana* L.). *Scientia Horticulturae* 44:215-225.
- 183 Downton, W.J.S., W.J.R. Grant, and B.R. Loveys. 1987. Carbon Dioxide Enrichment Increases Yield of Valencia Orange. *Australian Journal of Plant Physiology* 14:493-501.
- 2047 Eamus, D., C.A. Berryman, and G.A. Duff. 1993. Assimilation, Stomatal Conductance, Specific Leaf Area and Chlorophyll Responses to Elevated CO₂ of *Maranthes corymbosa* a Tropical Rain Forest Species. *Australian Journal of Plant Physiology* 20:741-755.
- 2071 Eamus, D., C.A. Berryman, and G.A. Duff. 1995. The Impact of CO₂ Enrichment on Water Relations in *Maranthes corymbosa* and *Eucalyptus tetrodonta*. *Australian Journal of Botany* 43:273-282.
- 2070 Eamus, D., G.A. Duff, and C.A. Berryman. 1995. Photosynthetic Responses to Temperature, Light, Flux-density, CO₂ Concentration and Vapour Pressure Deficit in *Eucalyptus tetrodonta* Grown under CO₂ Enrichment. *Environmental Pollution* 90:41-49.
- 208 El Kohen, A., J.-Y. Pontailier, and M. Mousseau. 1991. Effect of Doubling of Atmospheric CO₂ Concentration on Dark Respiration in Aerial Parts of Young Chestnut Trees (*Castanea sativa* Mill.). *Comptes Rendus des Sciences (Paris)* t. 312, Serie III:477-481.
- 209 El Kohen, A., H. Rouhier, and M. Mousseau. 1992. Changes in Dry Weight and Nitrogen Partitioning Induced by Elevated CO₂ Depends on Soil Nutrient Availability in Sweet Chestnut (*Castanea sativa* Mill.). *Annales des Sciences Forestieres* 49:83-90.
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- 221 Ferguson, J.J., W.T. Avigne, L.H. Allen, and K.E. Koch. 1986. Growth of CO₂-enriched Sour Orange Seedlings Treated with Gibberellins/Cytokinins. *Proceedings of the Florida State Horticultural Society* 99:37-39.
- 222 Fetcher, N., C.H. Jaeger, B.R. Strain, and N. Sionit. 1988. Long-term Elevation of Atmospheric CO₂ Concentration and the Carbon Exchange Rates of Saplings of *Pinus taeda* L. and *Liquidambar styraciflua* L. *Tree Physiology* 4:255-262.

- 2041 Garcia, R.L., S.B. Idso, G.W. Wall, and B.A. Kimball. 1994. Changes in net Photosynthesis and Growth of *Pinus eldarica* Seedlings in Response to Atmospheric CO₂ Enrichment. *Plant, Cell and Environment* 17:971-978.
- 233 Gaudillere, J.-P., and M. Mousseau. 1989. Short Term Effect of CO₂ Enrichment on Leaf Development and Gas Exchange of Young Poplars (*Populus euramericana* cv I 214). *Acta Oecologica/Oecologia Plantarum* 10:95-105.
- 2002 Gorissen, A., P.J. Kuikman, and H. van de Beek. 1995. Carbon Allocation and water Use in Juvenile Douglas Fir under Elevated CO₂. *New Phytologist* 129:275-282.
- 2036 Grulke, N.E., J.L. Hom, and S.W. Roberts. 1993. Physiological Adjustment of two Full-sib Families of Ponderosa Pine to Elevated CO₂. *Tree Physiology* 12:391-401.
- 2035 Gunderson, C.A., R.J. Norby, and S.D. Wullschlegel. 1993. Foliar Gas Exchange Responses of two Deciduous Hardwoods during 3 Years of Growth in Elevated CO₂: no Loss of Photosynthetic Enhancement. *Plant, Cell and Environment* 16:797-807.
- 290 Hollinger, D.Y. 1987. Gas Exchange and Dry Matter Allocation Responses to Elevation of Atmospheric CO₂ Concentration in Seedlings of three Tree Species. *Tree Physiology* 3:193-202.
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- 2123 Jarvis, P.G., H.S.J. Lee, and C.V.M. Barton. 1994. The Likely Impact of rising CO₂ and Temperature on European Forests. Institute of Ecology and Resource Management, University of Edinburgh.
- 2045 Johnsen, K.H. 1993. Growth and Ecophysiological Responses of Black Spruce Seedlings to Elevated CO₂ under Varied Water and Nutrient Additions. *Canadian Journal of Forest Research* 23:1033-1042.
- 2109 Johnson, D., D. Geisinger, R. Walker, J. Newman, J. Vose, K. Elliot, and T. Ball. 1994. Soil pCO₂, Soil Respiration, and Root Activity in CO₂-fumigated and Nitrogen-fertilized Pondersosa Pine. *Plant and Soil* 165:129-138.
- 340 Kaushal, P., J.M. Guehl, and G. Aussenac. 1989. Differential Growth Response to Atmospheric Carbon Dioxide Enrichment in Seedlings of *Cedrus atlantica* and *Pinus nigra* ssp. *Laricio* var. *Corsicana*. *Canadian Journal of Forest Research* 19:1351-1358.

- 362 Koch, K.E., P. Jones, W.T. Avigne, and L.H. Allen Jr. 1986. Growth, Dry Matter Partitioning, and Diurnal Activities of RuBP Carboxylase in Citrus Seedlings Maintained at Two Levels of CO₂. *Physiologia Plantarum* 67:477-484.
- 2121 Kubiske, M.E., and K.S. Pregitzer. 1994. Effect of Elevated CO₂ and Light Availability on the Photosynthetic Light Response of Trees of Contrasting Shade Tolerance. *Tree Physiology*; in press.
- 2120 Laboratorium Voor Plantecologie. 1992. Effect of Increased Atmospheric CO₂ Concentration on Primary Productivity and Carbon Allocation in Typical Belgian Forest Ecosystems. Progress report 1992.
- 2028 Lavola, A., and R. Julkunen-Tiitto. 1994. The Effect of Elevated Carbon Dioxide and Fertilization on Primary and Secondary Metabolites in Birch, *Betula pendula* (Roth). *Oecologia* 99:315-321.
- 2165 Lewis, J.D., R.B. Thomas, and B.R. Strain. 1994. Effect of Elevated CO₂ on Mycorrhizal Colonization of Loblolly Pine (*Pinus taeda* L.) Seedlings. *Plant and Soil* 165:81-88.
- 2224 Lindroth, R.L., K.K. Kinney, and C.L. Platz. 1993. Responses of Deciduous Trees to Elevated Atmospheric CO₂: Productivity, Phytochemistry, and Insect Performance. *Ecology* 74(3):763-777.
- 2065 Liu, S., and R.O. Teskey. 1995. Responses of Foliar Gas Exchange to Long-term Elevated CO₂ Concentrations in Mature Loblolly Pine Trees. *Tree Physiology* 15:351-359.
- 2069 Marek, M.V., J. Kalina, and M. Matouskova. 1995. Response of Photosynthetic Carbon Assimilation of Norway Spruce Exposed to Long-term Elevation of CO₂ Concentration. *Photosynthetica* 31:209-220.
- 2117 Mortensen, L.M. 1994. Effects of Carbon Dioxide Concentration on Assimilate Partitioning, Photosynthesis and Transpiration of *Betula pendula* Roth. and *Picea abies* (L.) Karst. Seedlings at two Temperatures. *Acta Agriculturae Scandinavica, Section B, Soil and Plant Sciences* 44:164-169.
- 2003 Mortensen, L.M. 1995. Effect of Carbon Dioxide Concentration on Biomass Production and Partitioning in (*Betula pubescens* Ehrh.) Seedlings at Different Ozone and Temperature Regimes. *Environmental Pollution* 87:337-343.
- 468 Mousseau, M. 1993. Effects of Elevated CO₂ on Growth, Photosynthesis and Respiration of Sweet Chestnut (*Castanea sativa* Mill.). *Vegetatio* 104/105:413-419.
- 470 Mousseau, M., and H.Z. Enoch. 1989. Carbon Dioxide Enrichment Reduces Shoot Growth in Sweet Chestnut Seedlings (*Castanea sativa* Mill.). *Plant, Cell and Environment* 12:927-934.
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- 505 Norby, R.J., and E.G. O'Neill. 1989. Growth Dynamics and Water Use of Seedlings of *Quercus alba* L. in CO₂-enriched Atmospheres. *New Phytologist* 111:491-500.

506 Norby, R.J., and E.G. O'Neill. 1991. Leaf Area Compensation and Nutrient Interactions in CO₂-enriched Seedlings of Yellow-poplar (*Liriodendron tulipifera* L.). *New Phytologist* 117:515-528.

503 Norby, R.J., E.G. O'Neill, W.G. Hood, and R.J. Luxmoore. 1987. Carbon Allocation, Root Exudation and Mycorrhizal Colonization of *Pinus echinata* Seedlings Grown under CO₂ Enrichment. *Tree Physiology* 3:203-210.

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2131 Norby, R.J., Wullschlegel, and C.A. Gunderson. 1996. Tree Responses to Elevated CO₂ and Implications for Forests. IN: *Carbon Dioxide and Terrestrial Ecosystems* (G.W. Koch and H.A. Mooney, eds.), Academic Press, New York, pp.1-21.

510 O'Neill, E.G., R.J. Luxmoore, and R.J. Norby. 1987. Increases in Mycorrhizal Colonization and Seedling Growth in *Pinus echinata* and *Quercus alba* in an Enriched CO₂ Atmosphere. *Canadian Journal of Forest Research* 17:878-883.

521 Overdieck, D. 1990. Effects of Elevated CO₂-concentration Levels on Nutrient Contents of Herbaceous and Woody Plants. IN: *The Greenhouse Effect and Primary Productivity in European Agro-ecosystems*; 5-10 April 1990; Wageningen, The Netherlands (J. Goudriaan, H. van Keulen, and H.H. van Laar, eds.), Pudoc, Wageningen, pp. 31-37.

550 Pettersson, R., and A.J.S. McDonald. 1992. Effects of Elevated Carbon Dioxide Concentration on Photosynthesis and Growth of Small Birch Plants (*Betula pendula* Roth.) at Optimal Nutrition. *Plant, Cell and Environment* 15:911-919.

2027 Pettersson, R., A.J.S. McDonald, and I. Stadenberg. 1993. Response of Small Birch Plants (*Betula pendula* Roth.) to Elevated CO₂ and Nitrogen Supply. *Plant, Cell and Environment* 16:1115-1121.

553 Polle, A., T. Pfirrmann, S. Chakrabarti, and H. Rennenberg. 1993. The Effects of Enhanced Ozone and Enhanced Carbon Dioxide Concentrations on Biomass, Pigments and Antioxidative Enzymes in Spruce Seedlings. *Plant, Cell and Environment* 16:311-316.

2110 Pregitzer, K.S., D.R. Zak, P.S. Curtis, M.E. Kubiske, J.A. Teeri, and C.S. Vogel. 1995. Atmospheric CO₂, Soil Nitrogen and Turnover of Fine Roots. *New Phytologist* 129(4):579-585.

582 Reekie, E.G., and F.A. Bazzaz. 1989. Competition and Patterns of Resource Use among Seedlings of Five Tropical Trees Grown at Ambient and Elevated CO₂. *Oecologia* 79:212-222.

2046 Reid, C.D., and B.R. Strain. 1994. Effects of CO₂ Enrichment on Whole-plant Carbon Budget of Seedlings of *Fagus grandifolia* and *Acer saccharum* in low Irradiance. *Oecologia* 98:31-39.

596 Rochefort, L., and F.A. Bazzaz. 1992. Growth Response to Elevated CO₂ in Seedlings of Four Co-occurring Birch Species. *Canadian Journal of Forest Research* 22:1583-1587.

- 2038 Roth, S.K., and R.L. Lindroth. 1994. Effects of CO₂-mediated Changes in Paper Birch and White Pine Chemistry on Gypsy Moth Performance. *Oecologia* 98:133-138.
- 644 Sharkey, T.D., F. Loreto, and C.F. Delwiche. 1991. High Carbon Dioxide and Sun/Shade Effects on Isoprene Emission from Oak and Aspen Tree Leaves. *Plant, Cell and Environment* 14:333-338.
- 655 Sionit, N., B.R. Strain, H. Hellmers, G.H. Riechers, and C.H. Jaeger. 1985. Long-term Atmospheric CO₂ Enrichment Affects the Growth and Development of *Liquidambar styraciflua* and *Pinus taeda* Seedlings. *Canadian Journal of Forest Research* 15:468-471.
- 666 Stewart, J.D., and J. Hoddinott. 1993. Photosynthetic Acclimation to Elevated Atmospheric Carbon Dioxide and UV Irradiation in *Pinus banksiana*. *Physiologia Plantarum* 88:493-500.
- 2042 Sullivan, J.H., and A.H. Teramura. 1994. The Effects of UV-B Radiation on Loblolly Pine. 3. Interaction with CO₂ Enhancement. *Plant, Cell and Environment* 17:311-317.
- 676 Surano, K.A., P.F. Daley, J.L.J. Houpis, J.H. Shinn, J.A. Helms, R.J. Palassou, and M.P. Costella. 1986. Growth and Physiological Responses of *Pinus ponderosa* Dougl. ex P. Laws. to Long-term Elevated CO₂ Concentration. *Tree Physiology* 2:243-259.
- 2005 Teskey, R.O. 1995. A Field Study of the Effects of Elevated CO₂ on Carbon Assimilation, Stomatal Conductance and Leaf Branch Growth of *Pinus taeda* Trees. *Plant, Cell and Environment* 18:565-573.
- 682 Thomas, R.B., D.D. Richter, H. Ye, P.R. Heine, and B.R. Strain. 1991. Nitrogen Dynamics and Growth of Seedlings of an N-fixing Tree (*Gliricidia sepium* (Jacq.) Walp.) Exposed to Elevated Atmospheric Carbon Dioxide. *Oecologia* 88:415-421.
- 2044 Tissue, D.T., R.B. Thomas, and B.R. Strain. 1993. Long-term Effects of Elevated CO₂ and Nutrients on Photosynthesis and Rubisco in Loblolly Pine Seedlings. *Plant, Cell and Environment* 16:859-865.
- 2032 Tschaplinski, T.J., R.J. Norby, and S.D. Wullschlegel. 1993. Responses of Loblolly Pine Seedlings to Elevated CO₂ and Fluctuating Water Supply. *Tree Physiology* 13:283-296.
- 2122 Vogel, C.S., and P.S. Curtis. 1995. Leaf Gas Exchange and Nitrogen Dynamics of N₂-fixing, Field-grown *Alnus glutinosa* under Elevated Atmospheric CO₂. *Global Change Biology* 1:55-61.
- 2068 Wang, K., S. Kellomaki, and K. Laitinen. 1995. Effects of Needle Age, Long-term Temperature and CO₂ Treatments on the Photosynthesis of Scots Pine. *Tree Physiology* 15:211-218.
- 2152 Williams, R.S., D.E. Lincoln, and R.B. Thomas. 1994. Loblolly Pine Grown under Elevated CO₂ Affects Early Instar Pine Sawfly Performance. *Oecologia* 98:64-71.

747 Wullschleger, S.D., and R.J. Norby. 1992. Respiratory Cost of Leaf Growth and Maintenance in White Oak Saplings Exposed to Atmospheric CO₂ Enrichment. *Canadian Journal of Forest Research* 22:1717-1721.

746 Wullschleger, S.D., R.J. Norby, and C.A. Gunderson. 1992. Growth and Maintenance Respiration in Leaves of *Liriodendron tulipifera* L. Exposed to Long-term Carbon Dioxide Enrichment in the Field. *New Phytologist* 21:515-523.

2004 Wullschleger, S.D., R.J. Norby, and P.J. Hanson. 1995. Growth and Maintenance Respiration in Stems of *Quercus alba* after Four Years of CO₂ Enrichment. *Physiologia Plantarum* 93:47-54.

7J45 Wullschleger, S.D., R.J. Norby, and D.L. Hendrix. 1992. Carbon Exchange Rates, Chlorophyll Content, and Carbohydrate Status of Two Forest Tree Species Exposed to Carbon Dioxide Enrichment. *Tree Physiology* 10:21-31.

2048 Yakimchuk, R., and J. Hoddinott. 1994. The Influence of Ultraviolet-B Light and Carbon Dioxide Enrichment on the Growth and Physiology of Seedlings of Three Conifer Species. *Canadian Journal of Forest Research* 24:1-8.

756 Ziska, L.H., K.P. Hogan, A.P. Smith, and B.G. Drake. 1991. Growth and Photosynthetic Response of Nine Tropical Species with Long-term Exposure to Elevated Carbon Dioxide. *Oecologia* 86:383-389.

APPENDIX C: FULL LISTING OF COMMENTS.DAT (FILE 6)

The number at the beginning of each entry corresponds to **PAP_NO**, the cited paper number, as defined in Sect. 9.

Listed are paper numbers, authors, CO₂ exposure facility, light, temperature, watering and nutrient conditions when available, location of experimental set-up, and comments. For the CO₂ exposure facilities, watering regimes, and locations the following distinctions were made:

CO₂-exposure facilities:

- BRANCH - branch chambers
- GC - indoor, controlled environment: growth chambers
- GH - sunlit greenhouses and chambers within greenhouses
- OTC - field-based open-top chambers
- SPAR - high tech soil-plant-atmosphere chambers

Watering regime:

- WW - well watered
- W - watered

Locations:

- NA - North America
- CA - Central America
- AU - Australia
- EU - Europe

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- 44 Arnone, J.A., III, and J.C. Gordon, 1990
GC
Light: 400 $\mu\text{mol}/\text{m}^2/\text{s}$ Photoperiod: 16h
Temperature: 26/20degC
Watering regime: WW/drip Humidity: 70%
Nutrients: daily 1/4 strength Hoagland
N Treatment: 0 vs 20 mg $\text{NH}_4\text{NO}_3\text{-N}/\text{l}$
NA: North Carolina
Root nodules from inoculation with Frankia cells
- 112 Brown, K.R., 1991
GC
Light: 400 $\mu\text{mol}/\text{m}^2/\text{s}$ at canopy level Photoperiod: 18h
Temperature: 22/17degC
Watering regime: WW 6 d/wk Humidity: 45%
Macronutrients 6d/wk; N Treatment: 0.155 vs 15.5 mM $\text{NH}_4\text{NO}_3\text{-N}$
NA: Canada: Alberta
SE estimated from confidence interval
- 121 Bunce, J.A., 1992
GH
Light: 27-49 $\text{mol}/\text{m}^2/\text{d}$
Temperature: 30-19degC
Watering regime: WW 2e or 3e day
fertile sandy loam+fertilizer/3 wks
NA: Maryland
SE and SD pers. comm.

- 150 Conroy, J.P., M. Kupperts, B. Kupperts, J. Virgona, and E.W.R. Barlow, 1988
GC
Light: 450 $\mu\text{mol}/\text{m}^2/\text{s}$ at top of plants Photoperiod: 16h
Temperature: 25/18degC
Watering regime: daily water
nutrients added; P treatment: P levels at 4.4 vs 40 mg/pot
AU
P-deficient needles of 0.7-0.8 mgP/gdrywt or 1-1.5 mgP/gdrywt
- 159 Couteaux, M.M., P. Bottner, H. Rouhier, and G. Billes, 1992
GC
soil with micro flora, fauna and litter
EU: S France
Se assumed
- 168 Curtis, P.S., and J.A. Teeri, 1992
OTC
Temperature: local+1.5/1/2degC
Watering regime: Precip+W
available N: 2.7ug/g soil
NA: N-Michigan
- 183 Downton, W.J.S., W.J.R. Grant, and B.R. Loveys, 1987
GH
Light: 600-350 $\mu\text{mol}/\text{m}^2/\text{s}$: top of plants-pot level Photoperiod: 10h

Temperature: 25/18degC
Watering regime: WW Humidity: 60-90%
1/2 strength Hoagland 2*wk
AU
fruit dry wt
- 184 Downton, W.J.S., W.J.R. Grant, and E.K. Chacko, 1990
GC
Light: 450 $\mu\text{mol}/\text{m}^2/\text{s}$ initially Photoperiod: 14-12h
Temperature: 30/22degC
Watering regime: WW daily Humidity: 50%
Oscomote each 3-4mo
AU
- 208 El Kohen, A., J.-Y. Pontailier, and M. Mousseau, 1991
OTC
EU: France
- 209 El Kohen, A., H. Rouhier, and M. Mousseau, 1992
GH
Watering regime: WW/drip
NPK Treatment: 0 NPK vs 0.82g N, 0.78gP, 0.4gK/month
EU: France
- 210 El Kohen, A., L. Venet, and M. Mousseau, 1993
GH
Temperature: local+-1.8degC
Watering regime: W daily
EU: France
N(#) Castanea from total # plants Castanea; from Fagus from F4

- 221 Ferguson, J.J., W.T. Avigne, L.H. Allen, and K.E. Koch, 1986
GH
Light: 85% from outside
Temperature: 31/23degC
Watering regime: WW
nutrients added: NPK 20:20:20; Peter's
NA: Florida
part of gibberellin and cytokinin treatment experiment
- 222 Fetcher, N., C.H. Jaeger, B.R. Strain, and N. Sionit, 1988
GH
Light: 1900 umol/m2/s for gas exchange measurements
Temperature controlled for 30yr average
NA: N Carolina
N(#) for stomatal conductance assumed same as for assimilation rate
- 233 Gaudillere, J.-P., and M. Mousseau, 1989
GC
Light: 250 umol/m2/s at top of canopy Photoperiod: 16h
Temperature: 22/15degC
Watering regime: WW Humidity: 50%
EU: France
- 290 Hollinger, D.Y., 1987
GC
Light: 700 umol/m2/s at top of canopy Photoperiod: 14h
Temperature: 20/10degC
Watering regime: WW Humidity: 70/90%
AU
SE of mass estimated
- 313 Idso, S.B., B.A. Kimball, and S.G. Allen, 1991
OTC
Watering regime: WW
nutrients added
NA: Arizona
- 314 Idso, S.B., and B.A. Kimball, 1991
OTC
Watering regime: WW
nutrients added
NA: Arizona
SD of mass estimated from area of F1
- 318 Idso, S.B., and B.A. Kimball, 1993
OTC
Watering regime: WW
nutrients added
NA: Arizona
Assimilation rate and N(#) estimated from F3
- 322 Idso, S.B., B.A. Kimball, and S.G. Allen, 1991
OTC
Watering regime: WW
nutrients added
NA: Arizona

- 340 Kaushal, P., J.M. Guehl, and G. Aussenac, 1989
GH
Light: 80% of natural outside light+160umol/m2/s at shoot level 6h/d
Temperature: local:10-23degC
Watering regime: WW Humidity: 80-90%
EU: France
SE/SD pers comm.
- 362 Koch, K.E., P. Jones, W.T. Avigne, and L.H. Allen Jr., 1986
GC
Light: 85% of incident light of outside
Temperature: 31/23degC
Watering regime: WW
nutrients added (Peter's)
NA: Florida
SE/SD pers comm
- 468 Mousseau, M., 1993
OTC
Temperature: 35-10/22-5degC
Watering regime: WW
nutrients added
EU: France
N(#) of mass assumed as in T1 pap 471
- 470 Mousseau, M., and H.Z. Enoch, 1989
OTC
Temperature: local+max4degC
Watering regime: WW/drip
nutrients added/yr
EU: France
- 502 Norby, R.J., C.A. Gunderson, S.D. Wullschleger, E.G. O'Neill, and
M.K. McCracken, 1992
OTC
soils potentially NP deficient
NA: 35.9degN 84.4degW
note on drought and nutrient deficiency
- 503 Norby, R.J., E.G. O'Neill, W.G. Hood, and R.J. Luxmoore, 1987
GC
Light: 540 umol/m2/s Photoperiod: 14h
Temperature: 25/7degC
Watering regime: W Humidity: 65%
soils potentially NP deficient
NA: Tennessee
potential soil nutrient deficient
- 504 Norby, R.J., E.G. O'Neill, and R.J. Luxmoore, 1986
GC
Light: 660 umol/m2/s at top of canopy Photoperiod: 14h
Temperature: 25/15degC
Watering regime: WW/drip Humidity: 65%
soils potentially NP deficient
NA: Tennessee
SE/SD for F1,T1,T2: e-mail; soil potentially nutrient deficient

- 505 Norby, R.J., and E.G. O'Neill, 1989
 GH
 Light: 580 $\mu\text{mol}/\text{m}^2/\text{s}$ Photoperiod: 14h
 Temperature: 26/10degC
 Watering regime: WW Humidity: 65/95%
 NPK treatment: 0 NPK vs 5,1.5,1.9mg N,P,K/pot/wk
 NA: Tennessee
 SE/SD: e-mail
- 506 Norby, R.J., and E.G. O'Neill, 1991
 GC
 Light: 600 $\mu\text{mol}/\text{m}^2/\text{s}$ Photoperiod: 14h
 Temperature: 26/12degC
 Watering regime: WW Humidity: 70/90%
 nutrients: 20.0.4.5,16.5 mg NPK+/wk ; later 2*wk
 NA: Tennessee
 N(#) from author
- 510 O'Neill, E.G., R.J. Luxmoore, and R.J. Norby, 1987
 GC
 Light: 450 $\mu\text{mol}/\text{m}^2/\text{s}$ Photoperiod: 14h
 Temperature: 26/10degC
 Watering regime: WW
 no nutrients added
 NA: Tennessee
- 521 Overdieck, D., 1990
 GC
 Watering regime: W as precip
 soils of average fertility
 EU: Germany: 52degN 8degE
- 550 Pettersson, R., and A.J.S. McDonald, 1992
 GC
 Light: 600 $\mu\text{mol}/\text{m}^2/\text{s}$ Photoperiod: 18h
 Temperature: 20degC
 hydroponics Humidity: 45%
 nutrient solution
 EU: Sweden
 N(#) 2-5: pers comm for gas exchange; as T1 for other measures
- 553 Polle, A., T. Pfirrmann, S. Chakrabarti, and H. Rennenberg, 1993
 GC
 controlled as for local environment
 Watering regime: WW:drip acidic mists
 Ozone Treatment: 0.02 vs 0.08 cm^3/m^3 : 24hrs/d like higher elevations
 EU: Germany:Bavaria
- 582 Reekie, E.G., and F.A. Bazzaz, 1989
 GH
 Light: local with 1000-1200 $\mu\text{mol}/\text{m}^2/\text{s}$ max levels
 Temperature: local 30/27degC
 Watering regime: WW
 monthly Peter's fertilization(20:20:20)
 Plant competition of tropical plants
 NA: Massachusetts

- 596 Rochefort, L., and F.A. Bazzaz, 1992
GH
Light: 900 $\mu\text{mol}/\text{m}^2/\text{s}$ clear days
Temperature: 28/20degC
Watering regime: WW Humidity: 73%
nutrients added each 2 weeks
NA: Massachusetts
- 644 Sharkey, T.D., F. Loreto, and C.F. Delwiche, 1991
GH
Light: 300-500 $\mu\text{mol}/\text{m}^2/\text{s}$ (gas measurements at 900 $\mu\text{mol}/\text{m}^2/\text{s}$)
Photoperiod: 15h
Temperature: 25/20degC Humidity: 70%/85%
NA: Wisconsin
Partly a shading and isoprene emission experiment
- 655 Sionit, N., B.R. Strain, H. Hellmers, G.H. Riechers, and C.H. Jaeger, 1985
GH
Temperature: night temp controlled
Watering regime: WW/drip Humidity: 70%
nutrients (Hoagland 1/15 strength daily)
NA: North Carolina
- 666 Stewart, J.D., and J. Hoddinott, 1993
GH
Light: 600 $\mu\text{mol}/\text{m}^2/\text{s}$ as maximum Photoperiod: 18h
Temperature: 15-32degC (local)
Watering regime: WW:2*wk
nutrients 1/wk
UVB Treatment: 0.005-0.03 vs 0.25-0.90 W/m2
NA: Canada: Alberta
- 676 Surano, K.A., P.F. Daley, J.L.J. Houppis, J.H. Shinn, J.A. Helms, R.J. Palassou, and M.P. Costella, 1986
OTC
Light: 80-90% from outside
Temperature: local+upto5degC
Watering regime: WW:3*wk+ Humidity: down to 10%
nutrients added/month: NPK + 2.2,1.8,1.3 g/pot/month
NA: California
- 682 Thomas, R.B., D.D. Richter, H. Ye, P.R. Heine, and B.R. Strain, 1991i
GC
Light: 1000 $\mu\text{mol}/\text{m}^2/\text{s}$ Photoperiod: 14h
Temperature: 29/23degC
Watering regime: WW Humidity: 70%
nutrients added daily with/without N
N Treatment: 0 vs 7.0 mM $\text{NH}_4\text{NO}_3\text{-N}$
NA: South Carolina
Seeds inoculated with Rhizobium
- 745 Wullschlegel, S.D., R.J. Norby, and D.L. Hendrix, 1992
OTC
gas exchange measures at 1300 $\mu\text{mol}/\text{m}^2/\text{s}$
NA: 35.9degN 84.4degW
Precip 169 cm at study site compared to 139 cm as 30 yr average

- 746 Wullschlegel, S.D., R.J. Norby, and C.A. Gunderson, 1992
 OTC
 NA: 35.9degN 84.4degW
- 747 Wullschlegel, S.D., and R.J. Norby, 1992
 OTC
 NA: 35.9degN 84.4degW
- 756 Ziska, L.H., K.P. Hogan, A.P. Smith, and B.G. Drake, 1991
 OTC
 Light: 740 umol/m2/s average; 1200umol/m2/s max Photoperiod: 10h
 Temperature: 36.5/21.2degC
 Watering regime: WW 2*day Humidity: 60%/85%
 nutrients added (Osmocote)
 CA: 83.9degN 9.2degW
 Values differ slightly from Table: pers comm
- 2002 Gorissen, A., P.J. Kuikman, and H. Van De Beek, 1995
 GC
 Light: 400 umol/m2/s Photoperiod: 16h
 Temperature: 18/14degC
 Watering regime: W Humidity: 70-80%
 EU: 52.2degN 5.8degE
- 2003 Mortensen, L.M., 1995
 GC
 Light: 18 mol/m2/day for temp treatment
 Light: 22 mol/m2/day for Ozone treatment Photoperiod: 24h
 Temperature: 17.3degC=control
 Watering regime: WW
 nutrients added
 2 Treatments: Ozone: 7 vs 62 nmol/mol for 8 hrs
 Temperature: 15.3 vs 20 degC
 EU: 60.8degN 11.5degE
- 2004 Wullschlegel, S.D., R.J. Norby, and P.J. Hanson, 1995
 OTC
 NA: 35.9degN 84.4degW
 Pisolithus tinctorius mycorrhizal inoculum; stem respiration
- 2005 Teskey, R.O., 1995
 BRANCH
 Light: 1200 umol/m2/s for gas exchange measurements
 Watering regime: irrigated
 NA: Georgia: 33.9degN 82.3degW
- 2026 Callaway, R.M., E.H. DeLucia, E.M. Thomas, and W.H. Schlesinger, 1994
 GC
 Light: 1000 umol/m2/s Photoperiod: 12h
 Temperature Treatment: 25/10degC vs 30/25degC
 Watering regime: WW Humidity: 45% during day
 nutrients 1/2 strength Hoagland
 NA: Nevada
- 2027 Pettersson, R., A.J.S. McDonald, and I. Stadenberg, 1993
 GC

2028 Lavola, A., and R. Julkunen-Tiitto, 1994
GH
Light: local -- 1137-175 $\mu\text{mol}/\text{m}^2/\text{s}$
Temperature: 22/15degC
NKP Treatment: 0 vs 500 kg/ha
EU: Finland

2032 Tschaplinski, T.J., R.J. Norby, and S.D. Wullschleger, 1993
GC
Light: 720 $\mu\text{mol}/\text{m}^2/\text{s}$ Photoperiod: 14h
Temperature: 26/16degC
H2O Treatment: weekly vs biweekly watering Humidity: 85-90%
fertilized/month (Peter's NPK 20:20:20)
NA: Tennessee

2035 Gunderson, C.A., R.J. Norby, and S.D. Wullschleger, 1993
OTC
Light: 1100-2300 $\mu\text{mol}/\text{m}^2/\text{s}$ for gas exchange measurements
Temperature: local
Watering regime: precip
NA: 35.9degN 84.4degW

2036 Grulke, N.E., J.L. Hom, and S.W. Roberts, 1993
GC
Light: 713 $\mu\text{mol}/\text{m}^2/\text{s}$ at canopy height Photoperiod: 12hr later 14h
Temperature: 25/19degC
Watering regime: WW Humidity: 46-57%/81%
fertilized weekly
NA: California

2037 Bazzaz, F.A., S.L. Miao, and P.M. Wayne, 1993
GH
Light: 37% and 75 % of full sun
Temperature: 30/23degC
2 Treatments: Light: 37% and 75% of full sun
Fertilizer: 0.18 and 1.8 g Osmote
NA: Massachusetts

2038 Roth, S.K., and R.L. Lindroth, 1994
GC
Light: 501 $\mu\text{mol}/\text{m}^2/\text{s}$ Photoperiod: 15h
Temperature: 25/20degC
Watering regime: WW/drip Humidity: 70/85%
fertilized 1/2 strength Hoagland 2*per day
NA: Wisconsin

2039 Curtis, P.S., C.S. Vogel, K.S. Pregitzer, D.R. Zak, and J.A. Teeri, 1995
OTC
Light: gas exchange measures at 1800 $\mu\text{mol}/\text{m}^2/\text{s}$
Temperature: local

- Watering regime: WW
 Soil Treatment: 45 vs 346 ug N/g/d N mineralization in soils
 64 vs 110 mg extractable PO₄/kg soil
 NA: N-Michigan
- 2041 Garcia, R.L., S.B. Idso, G.W. Wall, and B.A. Kimball, 1994
 OTC
 Watering regime: WW
 fertilized
 NA: Arizona
- 2042 Sullivan, J.H., and A.H. Teramura, 1994
 GH
 Light: ~80-85% of outdoors
 Temperature: 27/23degC
 Watering regime: WW/daily
 fertilized 1/2 strength Hoagland
 UVB Treatment: 8 hrs daily 8.8 vs 13.8 kJ/m²
 NA: Maryland
 SE for T1 SE for F1 (e-mail)
- 2043 Cipollini, M.L., B.G. Drake, and D. Whigham, 1993
 OTC
 Light: 10-100-occasionally 1000 umol/m²/min
 NA: Maryland
- 2044 Tissue, D.T., R.B. Thomas, and B.R. Strain, 1993
 OTC
 Watering regime: precip
 1/2 strength Hoagland 2*week
 2 Treatments: High NP: 7mol/m² NH₄NO₃+1mol/m³ PO₄;
 low P: same N+0.2mol/m³P;
 low N: 1mol/m³NH₄NO₃+1mol/m³PO₄
 NA: North Carolina
 N(#) in T1 does not match text
- 2045 Johnsen, K.H., 1993
 GC
 Light: 450 umol/m²/s at bench height Photoperiod: 19h
 Temperature: 20/15degC
 watering treatment Humidity: 70/90%
 treatment within 1/3 strength Ingestad
 2 Treatments:
 WW vs drought cycles (fertilized with 8 mL 300 ppmN: Ingestad);
 Fertilization: 6 mL/wk then 12 mL after 71 days vs 12mL,
 18 mL, 24 mL, 32 mL after day 1, 42, 71 and 104
 NA: Canada: Ontario
- 2046 Reid, C.D., and B.R. Strain, 1994
 GC
 Light: 65 umol/m²/s Photoperiod: 12h
 Temperature: 19/15degC
 Watering regime: WW daily
 1/4 strength Hoagland
 NA: North Carolina
- 2047 Eamus, D., C.A. Berryman, and G.A. Duff, 1993

- OTC
 Light: ambient local
 Temperature: local-up to 1.5degC
 AU
- 2048 Yakimchuk, R., and J. Hoddinott, 1994
 GC
 Light: 150 umol/m2/s+2hrs 40 umol/m2/s Photoperiod: 18h
 Temperature: 20/18degC
 Watering regime: WW Humidity: 65%
 fertilized weekly
 Ozone treatment: 1.1 uW/cm2 vs 150 uW/cm2 8hrs/day
 NA: Canada: Alberta
 potsize: pers. com.
- 2065 Liu, S., and R.O. Teskey, 1995
 BRANCH
 Light: gas exchange at 1000-2000 umol/m2/s
 Temperature: 16.5degC
 Watering regime: W+precip
 low to medium soil fertility
 NA: 33.9degN 83.3degW
 mature trees, low fertility site
- 2068 Wang, K., S. Kellomaki, and K. Laitinen, 1995
 OTC
 Temperature treatment: ambient vs hot=amb+2degC in summer, amb+5-20degC
 Watering regime: W+precip
 sandy soil
 EU: 62.8degN 30.9degE
 chamber around coniferous saplings; elevated CO2 only during daytime
- 2069 Marek, M.V., J. Kalina, and M. Matouskova, 1995
 OTC
 native Coniferous
 EU: 49.5degN 18.5degW
 native coniferous; elevated CO2 level is saturating level
- 2070 Eamus, D., G.A. Duff, and C.A. Berryman, 1995
 SPAR
 Light: 68% of full
 Temperature: local minus upto 3degC
 Watering regime: WW/drip
 Osmocote in soils
 AU
- 2071 Eamus, D., C.A. Berryman, and G.A. Duff, 1995
 SPAR
 Light: 66% of full
 Temperature: local minus upto 3degC
 Watering regime: WW 2*day
 fertilized each 2 weeks
 AU
- 2109 Johnson, D., D. Geisinger, R. Walker, J. Newman, J. Vose, K. Elliot,
 and T. Ball, 1994
 OTC

- Watering regime: WW
 N treatment: 0 vs 20 g/m²/yr ammonium sulfate
 NA: California
 SE vs SD estimates F5; chamber description in Ball et al (1992)
- 2110 Pregitzer, K.S., D.R. Zak, P.S. Curtis, M.E. Kubiske, J.A. Teeri,
 and C.S. Vogel, 1995
 OTC
 Watering regime: WW
 Soil treatment: 45 vs 348 ug N/g/d N mineralization in soils;
 64 vs 110 mg extractable PO₄/kg soil
 NA: N-Michigan
- 2117 Mortensen, L.M., 1994
 GC
 Light treatment: 15 mol/m²/d then 22 mol/m²/d for birch,
 21 mol/m²/d for spruce
 Photoperiod: 24h
 Temperature Treatment: 15.3 vs 20.0 degC
 Watering regime: WW 600 vs 1000 Pa as wvpd at 15.3 vs 20degC
 fertilized, see Mortensen, 1994
 EU: Norway
- 2120 Laboratorium Voor Plantecologie 1992
 GC
 Light: 270umol/m²/s Photoperiod: 16h
 Temperature: 22/17.5degC
 Watering regime: WW/drip Humidity: 65%
 fertilized at optimal levels
 EU: Belgium
- 2121 Kubiske, M.E., and K.S. Pregitzer, 1994
 OTC
 Light Treatment: low and high; understory imitation
 NA: N-Michigan
- 2122 Vogel, C.S., and P.S. Curtis, 1995
 OTC
 Temperature: local+2.6degC
 fertilized with 4.5 g/m² N
 NA: 45.6degN 84.7degW
 nodule inoculations
- 2123 Jarvis, P.G., H.S.J. Lee, and C.V.M. Barton, 1994
 OTC
 Light and temperature not reported for growth
 EU: Scotland
 N(#) pers comm for T2
- 2129 Curtis, P.S., D.R. Zak, K.S. Pregitzer, and J.A. Teeri, 1994
 OTC
 Temperature: local+3degC
 Watering regime: precip+W
 All rootboxes received 4.5 g/m² N; similar to natural dry oak forest
 NA: N-Michigan
- 2131 Norby, R.J., Wullschleger, and C.A. Gunderson, 1996

- OTC
NA: Tennessee
Sample size and SD from pers comm.
- 2152 Williams, R.S., D.E. Lincolnm, and R.B. Thomas, 1994
OTC
Watering regime: precip+W
modified Hoagland 7mmol NH₄NO₃+1mmolPO₄ /wk
NA: North Carolina
- 2165 Lewis, J.D., R.B. Thomas, and B.R. Strain, 1994
GH
Temperature: 28/17 - 28/22degC
Watering regime: WW
1/2 strength Hoagland/wk; P Treatment: 0.083mM KH₂PO₄ vs 0.5mM KH₂PO₄:
P stress
NA: North Carolina
inoculation *Pisolithus tinctorius* vs not
- 2186 Bassow, S.L., K.D.M. McConnaughay, and F.A. Bazzaz, 1994
GH
Light: natural+supplement when light<500umol/m²/s i
Photoperiod local: 6-19h
Temperature: 28/22degC
Fertilizer Treatment: 0.12 vs 1.2 g Osmocote > N input of
40 vs 400 kg N/ha/yr; 3 mo after initial Osmocote
weekly 200 ml Peter's solution (20:20:20) at
0.042 v s 0.42 g/l/wk
NA: Massachusetts
N(#) F1: pers. comm
- 2217 Berryman, C.A., D. Eamus, and G.A. Duff, 1993
OTC
Light: 65% of full
Temperature: 29.7degC
Watering regime: WW:3*day
nutrients added; also 5 g low P Osmocote
AU
- 2223 Bazzaz, F.A., and S.L. Miao, 1993
GH
Light treatment: full gap light vs 37% thereof
Temperature: 27/20 > 30/23degC
Watering regime: WW
nutrient treatment: N equivalents of 40 vs 400 kg N/ha/yr i.e.
0.18 vs 1.8 g Osmocote/pot
NA: Massachusetts
- 2224 Lindroth, R.L., K.K. Kinney, and C.L. Platz, 1993
GH
Light: 490 mol/m²/s 70cm above pots Photoperiod: 15h
Temperature: 25/20degC
Watering regime: WW/drip Humidity: 70/80%
1/2 strength Hoagland
NA: Wisconsin
native mycorrhiza in soil

APPENDIX D: REPRINT OF PERTINENT LITERATURE

Curtis, P. S., and X. Wang. 1998. A meta-analysis of elevated CO₂ effects on woody plant mass, form, and physiology. *Oecologia* 113:299-313.

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Peter S. Curtis · Xianzhong Wang

A meta-analysis of elevated CO₂ effects on woody plant mass, form, and physiology

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Abstract Quantitative integration of the literature on the effect of elevated CO₂ on woody plants is important to aid our understanding of forest health in coming decades and to better predict terrestrial feedbacks on the global carbon cycle. We used meta-analytic methods to summarize and interpret more than 500 reports of effects of elevated CO₂ on woody plant biomass accumulation and partitioning, gas exchange, and leaf nitrogen and starch content. The CO₂ effect size metric we used was the log-transformed ratio of elevated compared to ambient response means weighted by the inverse of the variance of the log ratio. Variation in effect size among studies was partitioned according to the presence of interacting stress factors, length of CO₂ exposure, functional group status, pot size, and type of CO₂ exposure facility. Both total biomass (W_T) and net CO₂ assimilation (A) increased significantly at about twice ambient CO₂, regardless of growth conditions. Low soil nutrient availability reduced the CO₂ stimulation of W_T by half, from +31% under optimal conditions to +16%, while low light increased the response to +52%. We found no significant shifts in biomass allocation under high CO₂. Interacting stress factors had no effect on the magnitude of responses of A to CO₂, although plants grown in growth chambers had significantly lower responses (+19%) than those grown in greenhouses or in open-top chambers (+54%). We found no consistent evidence for photosynthetic acclimation to CO₂ enrichment except in trees grown in pots <0.5 l (–36%) and no significant CO₂ effect on stomatal conductance. Both leaf dark respiration and leaf nitrogen were significantly reduced under elevated CO₂ (–18% and –16% respectively, data

expressed on a leaf mass basis), while leaf starch content increased significantly except in low nutrient grown gymnosperms. Our results provide robust, statistically defensible estimates of elevated CO₂ effect sizes against which new results may be compared or for use in forest and climate model parameterization.

Key words Elevated CO₂ · Meta-analysis · Woody plants

Introduction

Forested ecosystems cover approximately 35% of the world's land surface and may accounted for as much as 70% of terrestrial net primary productivity (Meyer and Turner 1992; Mellilo et al. 1993). Their future prospects are of concern to many millions of people who rely on forests directly or indirectly for food, fuel, building material, and the myriad of ecological goods and services they provide. Increasing atmospheric CO₂ has the potential to fundamentally alter forest ecosystem functioning through effects on tree growth, resource use, and species interactions (Eamus and Jarvis 1989). Because of their prominent role in the global carbon cycle, forests may in turn affect the rate of atmospheric CO₂ increase (Walker and Kasting 1992). The extent and manner with which trees respond to changes in CO₂ concentration has thus been of interest to the forest products industry, natural resource managers, ecologists, and atmospheric scientists.

Empirical research on CO₂ effects in forests has proceeded along numerous lines of inquiry, but the great majority of studies share certain common features. In these experiments, the CO₂ treatments to which plants are exposed are typically ambient (c. 35 Pa) and twice ambient (c. 70 Pa) CO₂ partial pressure with additional levels occasionally included. Atmospheric CO₂ levels are expected to reach 70 Pa in the next 100–150 years (Houghton et al. 1990). Elevated CO₂ treatments are imposed as a single step change from ambient CO₂ levels

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by adding 100% CO₂ to the input air supply of controlled environment growth chambers (GC), greenhouses (GH) or field-based open-top chambers (OTC) (Schulze and Mooney 1994). First-year seedlings or young plants propagated from cuttings are used most often as experimental material, although occasionally mature trees or branches of trees are studied (e.g., Cipollini et al. 1993; Liu and Teskey 1995). Of considerable interest to workers studying elevated CO₂ has been the effect of interacting environmental variables on the magnitude of CO₂ responses by trees. Consequently, experiments are often set up as two-way factorial designs, with CO₂ crossed with another factor such as nitrogen availability or ozone level. While the specific objectives of individual researchers and the duration of their experiments vary widely, basic measures of plant growth (e.g., biomass, leaf area), physiological performance (e.g., gas exchange), and tissue composition (e.g., leaf N content) are often reported.

These common design and measurement characteristics are an advantage when attempting to integrate results across studies. Nonetheless (and not surprisingly), there is a substantial degree of variation in the magnitude of reported CO₂ effects on trees, ranging from significant inhibition of growth by elevated CO₂, to enhancements in excess of 500% relative to ambient grown plants (McGuire et al. 1995). An important goal in reviews of this work is to partition this variation into that which can be explained by treatment effects common to groups of studies and that which is due to sampling error or other idiosyncratic effects specific to individual studies. For example, in a set of 102 measurements of total tree biomass, growth at elevated CO₂ resulted in an average weight gain of 29% across a range of from -31% (inhibition) to +284% (stimulation) (Fig. 1). One obvious way to partition this data set is by whether or not another factor that could affect the magnitude of the CO₂ response was included in the experimental design of each study. While this narrows the range of responses within groups, there remains both broad overlap in responses between groups and substantial variation within groups (Fig. 1). Further partitioning of groups might be according to factors not considered explicit treatments by the primary researchers but that could help account for this remaining variation, such as length of study, size of pots in which plants were grown, or "quality" of the science being reported (however that might be defined). One objective of such an exercise is to identify groups of studies whose combined results can lead to meaningful generalizations regarding the response parameter under study, in this case percent change in whole plant biomass.

In a traditional narrative literature review, results from those individual studies that are judged by the reviewer to be representative or otherwise noteworthy are summarized qualitatively, serving as the basis for generalization, extrapolation, or other objectives of the reviewer. Although the narrative approach has been, and will no doubt continue to be, of fundamental importance

Fig. 1 Percent change in total (above + belowground) biomass in woody plants grown under elevated compared to ambient CO₂ as reported in 102 different experiments. Results are grouped according to whether plants were exposed either to no stress (*None*), low nutrient availability (*Fert*), low light levels (*Light*), high ozone (*O3*), high UVB (*UVB*) or low or high temperature (*Temp*) in addition to the CO₂ treatment. Mean $\pm$ 1 SE calculated from the log-transformed response ratio

in synthesizing many types of scientific research, it is inadequate for the quantitative integration of large numbers of research reports (Cooper and Rosenthal 1980). Review of the literature on elevated CO₂ has for some time included both narrative reviews and quantitative summaries, with the latter in some cases involving results from hundreds of published reports (e.g., Cure 1985; Idso and Idso 1994). Quantitative summaries have been important in model parameterization and in establishing benchmarks against which other work can be compared (e.g., Kimball 1983). Unfortunately, their utility has been hampered by *ad hoc* sampling and analysis methods that do not allow statistically robust hypothesis testing or comparison among groups.

Statistical methods have been developed for the quantitative integration of research results from independent experiments (Hedges and Olkin 1985; Cooper and Hedges 1994). Such formal integration, or meta-analysis, of data has been conducted extensively in the social and medical sciences (Mann 1994) and has recently been extended to ecological studies (Arnqvist and Wooster 1995). The advantage of meta-analysis over quantitative methods previously used in reviews of work on elevated CO₂ is the ability to place confidence limits

around effect size estimates, to discriminate statistically among subsets of the data, and to compare critically the variance within and among studies. More generally, it requires of reviewers the same rigor in sampling and analysis as is required of primary researchers.

Here, we used meta-analytic methods to summarize and interpret 508 reports of CO₂ effects on tree physiology and growth taken from 79 separate publications and 59 species (Appendices 1 and 2). This paper extends the work of Curtis (1996) and introduces a new meta-analytic metric, the weighted log ratio. Our review has two primary objectives: (1) to provide estimates of the magnitude and significance of elevated CO₂ effects on tree biomass accumulation and partitioning, gas exchange, and leaf nitrogen and starch content; and (2) to determine how experimental design factors or taxonomic affinity affects the magnitude of these CO₂ responses. We do not address the issue of how, or under what conditions, these results may be scaled up to predict the behavior of entire forests or biomes. As with any effort to integrate and interpret scientific information, considerable caution is advised when extrapolating beyond the range of ones data.

Methods

Database development

Bibliographic resources used in developing the meta-database were Strain and Cure (1986, 1994), and the *Current Advances in Plant Science* and *Current Contents* citation indices. Our literature survey was intended to be comprehensive, with all published studies conducted with woody species available through December 1995 included. We extracted information on 36 response variables, ten of which will be reported on here. Those are: total above- + below-ground biomass (W_T), below-ground biomass (W_B), stem biomass (W_S), total leaf biomass (W_L), light saturated net CO₂ assimilation (A), photosynthetic acclimation or downregulation (A_{accl}), stomatal conductance (g_s), leaf dark respiration (R_d , expressed on a leaf mass basis), leaf starch concentration (St_L , expressed on a mass basis), and leaf nitrogen concentration (N_L , expressed on a mass basis).

For results from any given study to be included in the meta-database there was a general requirement that response means

($\bar{X}_e$, $\bar{X}_a$), standard deviations (S_e , S_a) (or standard errors), and sample sizes (n_e , n_a) of elevated and ambient CO₂ grown plants respectively be reported as numerical or graphical data in the manuscript, or be available by personal communication. This requirement was necessary for the weighting of response ratios according to precision of the primary results. Given the unevenness with which these basic statistical measures were reported, this requirement resulted in many published observations being excluded from consideration. An additional requirement was that ambient treatments be below 40 Pa CO₂ and elevated treatments be between 60 and 80 Pa CO₂. Most meta-analytic methods require that individual observations be statistically independent so only one measurement point per treatment per study was used. In most cases these were data obtained following the longest period of CO₂ exposure reported in that study. "Treatment" included species identity as well as crossed experimental factors interacting with CO₂ such as ozone level or soil nutrient availability. Thus, a study examining a number of species in a multi-factorial design could contribute several observations for each response variable measured (e.g., Bazzaz and Miao 1993; Kubiske and Pregitzer 1996).

We were specifically interested in how different categorical variables influenced the magnitude of elevated CO₂ responses. The five categorical variables whose effects we discuss here are, environmental stress factors (Stress), plant functional group (Func Grp), length of CO₂ exposure (Time), pot size (Pot), and type of exposure facility (Method) (Table 1). We required information on each of these variables for a study to be included in the database. For purposes of meta-analysis we established discrete levels for each variable and coded each observation accordingly. In most cases coding decisions were unambiguous but occasionally subjective interpretations were required to place a particular experimental design or treatment within one of these categorical levels. For example, field studies having "native soil" were considered unstressed unless some stress factor had been clearly identified by the author. Low N studies with N₂-fixing plants and low P studies with mycorrhizal plants were also considered unstressed. The basis for coding decisions was described in more detail by Curtis (1996). The Stress factor associated with each study is also listed in Appendix 2.

Meta-analysis of response ratios

Meta-analytic studies depend on some estimate of treatment effect size, commonly the magnitude of an experimental treatment mean (in this case, $\bar{X}_e$) relative to the control treatment mean (in this case, $\bar{X}_a$) (Cooper and Hedges 1994). In a previous meta-analysis of the elevated CO₂ literature, Curtis (1996) used the standardized difference between experimental and control means, the so-called d -index, as the estimate of CO₂ effect size from a particular study. While the d -index had certain statistical advantages and was widely used in the social and medical sciences, it was not an effect size

Table 1 Categorical variables used in describing experimental conditions, and the values (levels) they could assume in the analysis of between-group heterogeneity (Q_b). Note that Time and Pot were

entered as continuous variables in the meta-database. There were additional Stress levels encountered in the CO₂ literature but not considered in this analysis

Categorical variable	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8
Stress	None (optimal growth conditions)	Fert (low N or P treatment)	Light (low light treatment)	O ₃ (high ozone treatment)	UVB (high UV-B treatment)	Temp (low or high temperature treatment)	H ₂ O (drought treatment)	Comp (competition treatment)
Time	≤59 days	60–99 days	100–365 days	> 365 days				
Func Grp	Angiosperm	Gymnosperm	N ₂ fixer					
Pot	≤0.5 l	0.6–2.4 l	2.5–9 l	≥10 l	In ground			
Method	GC (indoor growth chamber)	GH (greenhouse)	OTC (open-top chamber)	FACE (free-air CO ₂ enrichment)	Branch (branch chamber)			

metric commonly used to assess responses to elevated CO₂. A much more common effect size metric in elevated CO₂ studies (as well as in other areas of ecology) is the response ratio, $r = \bar{X}_e/\bar{X}_a$. An impediment to the meta-analysis of response ratios, however, has been poor understanding of the sampling distribution of r and the lack of any formal statistical methods for its integration across independent studies.

L.V. Hedges, J. Gurevitch, and P.S. Curtis (unpublished ms) have developed new statistical methods for the meta-analysis of response ratios. These methods have been incorporated into statistical software for performing meta-analyses (MetaWin, Rosenberg et al. 1996) and this software was used in the present study. In brief, r first must be log-transformed such that $lr = \ln(r) = \ln(\bar{X}_e) - \ln(\bar{X}_a)$. If $\bar{X}_e$ and $\bar{X}_a$ are normally distributed and $\bar{X}_a$ is unlikely to be negative, then lr is approximately normally distributed with a mean of approximately the true response log ratio and variance, v , equal to

$$v = \frac{S_e^2}{n_e \bar{X}_e^2} + \frac{S_a^2}{n_a \bar{X}_a^2} \quad (1)$$

The 95% confidence interval for an individual log response ratio is then

$$95\% \text{ CI} = lr - 1.96\sqrt{v} \text{ to } lr + 1.96\sqrt{v} \quad (2)$$

and the corresponding confidence limits for the unlogged response ratio obtained by computing their respective antilogs.

In summarizing results from independent studies, weighted means are normally used since individual experiments often differ in their statistical precision (e.g., Fig. 1). Giving greater weight to experiments whose estimates have greater precision (i.e., smaller standard error) will increase the precision of the combined estimate. The weighted mean log ratio (lr^*) that produces the greatest precision (minimum variance) is

$$lr^* = \frac{\sum_{i=1}^k w_i^* lr_i}{\sum_{i=1}^k w_i^*} \quad (3)$$

where the weighting factor $w_i^* = 1/(v_i + \hat{\sigma}_\lambda^2)$ is the reciprocal of the total variance of lr_i . Here, a mixed model analysis is assumed in which the pooled within-class variance, $\hat{\sigma}_\lambda^2$, is added to v (Gurevitch and Hedges 1993).

Because each of the k individual log ratios is approximately normally distributed, the weighted mean is normally distributed with confidence intervals calculated as in Eq. 2, where the standard error is

$$S(lr^*) = \sqrt{1 / \sum_{i=1}^k w_i^*} \quad (4)$$

Partitioning variance within and between groups

With meta-analysis, one can test whether categorical groups (e.g., angiosperms or gymnosperms) are homogeneous with respect to effect size (i.e., that observed differences in lr among studies are due to sampling error), and whether there are significant differences in mean response between those groups (Hedges and Olkin 1985). In a procedure analogous to the partitioning of variance in analysis of variance, the total heterogeneity for a group of comparisons (Q_T) is partitioned into within-class heterogeneity (Q_w) and between-class heterogeneity (Q_b), such that $Q_T = Q_w + Q_b$. The Q statistic follows a chi-square distribution, with $k-1$ degrees of freedom.

A central goal of our meta-analysis was to understand the source of variation in CO₂ effect size among studies and to determine whether particular growth conditions or groups of species elicited quantitatively different responses. The approach we took was to partition total heterogeneity (Q_T) within and between levels of each categorical variable. For example, the categorical variable Time (= length of the CO₂ exposure) was partitioned into short (<59 days), medium (60–99 days), long (100–365 days) and very

long (>365 days) exposure periods (levels). Grouping the data according to Time classes we could test whether there was significant between-group heterogeneity with respect to CO₂ exposure duration. This is analogous to examining the significance level of a particular source of variation in a conventional analysis of variance.

Partitioning of variance proceeded in two steps. First, between-group heterogeneity (Q_b) for each categorical variable was examined across all data for a given response variable. Second, the data set was subdivided according to levels of those categorical variables revealing significant Q_b , and the first step repeated. Mean log ratios were calculated when the number of categorical variables exhibiting significant Q_b had been reduced to one or zero, suggesting no further partitioning of the dataset was justified. Means were considered to be significantly different from one another if their 95% CIs were non-overlapping and were significantly different from zero if the 95% CI did not overlap zero (Gurevitch and Hedges 1993).

Results

Biomass responses to elevated CO₂ were strongly affected by environmental stress factors and to a lesser degree by duration of CO₂ exposure and functional group affiliation (Table 2). Total biomass increased significantly at high CO₂ (+28.8%, $k=102$, Fig. 1) but there were also significant differences among stress categories (Fig. 2). Plants grown under nutrient stress showed only half the percentage growth stimulation (+15.5%) of plants with no stress treatment (+30.9%) and one-third that of plants grown under low light (+52.3%). Examination of each of these sub-groups for other significant categorical divisions (e.g., Pot or Time) showed no additional significant between-group heterogeneity (Q_b) (data not shown). This suggests that *across all studies*, there were significant differences in CO₂ response among plants grown under different stress regimes, but not, for example, among those grown in different pot size classes. The small number of studies incorporating environmental stresses other than Fert and Light (e.g., O₃, UVB, Temp) resulted in large confidence

Table 2 Between-group heterogeneity (Q_b) for CO₂ effect size across five categorical variables for total biomass (W_T), below-ground biomass (W_B), stem biomass (W_S), leaf biomass (W_L), net CO₂ assimilation (A), photosynthetic acclimation (A_{accl}), stomatal conductance (g_s), leaf dark respiration (R_d), leaf starch concentration (St_L), and leaf nitrogen concentration (N_L). The categorical variables and their levels are as in Table 1. Each response variable was represented by k studies

Variable	k	Func Grp	Time	Pot	Method	Stress
W_T	102	0.23	3.75	1.13	2.03	21.74***
W_B	64	2.23	9.40*	3.20	1.40	9.23*
W_S	47	1.94	4.88	1.24	1.10	8.47*
W_L	50	5.97*	5.60	2.58	2.20	11.80**
A	79	0.71	6.19	10.33*	7.91*	1.20
A_{accl}	28	0.24	3.64	9.57*	3.64	2.23
g_s	48	0.22	2.32	4.15	2.14	1.34
R_d	16	0.26	1.46	3.15	2.46	0.38
St_L	17	5.96*	6.58	6.65*	4.84	7.46**
N_L	41	0.32	6.39	1.85	1.35	0.03

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

limits and little power to draw statistical inferences regarding the relative magnitude of their mean effects.

Belowground biomass responses to CO_2 were highly significant overall (+38%, $k=64$) but were affected by environmental stress factors and length of the CO_2 exposure (Table 2). Thus, there were significant time effects (across all stress types), but also significant stress effects (across all time categories). Further partitioning of this dataset showed that for plants exposed to no stress treatment, time categories were no longer significantly different nor was there any other significant Q_b

Fig. 2 The effect of environmental stress on the biomass response of trees to elevated CO_2 . Plants were exposed either to no stress (None), low nutrient availability (Fert), low light levels (Light), high ozone (O3), high UVB (UVB) or low or high temperature (Temp). Mean $\pm$ 95% confidence interval (k)

(Table 3). It should be noted that as the data set was divided, not every categorical variable level was represented in each sub-group. For example, there was no pot level 5 (=planting in ground) represented in the 36 studies reporting W_B measurements in unstressed trees. In this group, W_B increased 41.5% under elevated CO_2 (Fig. 3).

In contrast to the unstressed group, among all remaining W_B studies (i.e., those including Fert, UVB, and

Fig. 3 The effect of elevated CO_2 on biomass allocation to leaves (W_L), stem (W_S), or roots (W_B) in plants grown with (Fert, UVB, Light) or without (None) interacting stress conditions. Mean $\pm$ 95% confidence interval (k)

Table 3 Between-group heterogeneity (Q_b) for subgroups of response variables presented in Table 2. Data sets were partitioned according to the variable level in bold type, and Q_b for all categories

Var	k	Stress level	Stress Q_b	Time level	Time Q_b	Func Grp level	Func Grp Q_b	Pot level	Pot Q_b	Method level	Method Q_b
W_B	36	None	—	All	5.26	Angio, Gymno	0.01	1-4	1.77	All	0.05
W_B	25	Fert, UVB, Light	5.58	3,4	7.83**	Angio, Gymno	4.62*	1-3, 5	4.35	All	4.72
W_B	22	Fert, UVB, Light	12.44**	3	—	Angio, Gymno	2.33	1-3	0.61	GC, GH	0.66
W_L	37	None	—	All	4.78	Angio, Gymno	2.05	All	4.53	All	0.95
W_L	10	Fert, UVB	5.38*	3	—	Angio, Gymno	6.69**	1-3	8.06*	GC, GH	3.98*
A	59	All	0.90	All	5.78	All	0.12	All	11.31*	GH, OTC	2.78
A	50	All	0.80	All	8.94*	All	0.59	3-5	4.49	GH, OTC	0.42
A	19	None, Fert	1.03	1-3	0.43	All	4.04	1-4	2.54	GC	—
A_{acc}	24	None	—	All	2.04	All	0.40	2-5	0.53	GC, GH, OTC	1.15
St_L	12	None, Fert	0.90	1-3	0.87	Angio	—	3-5	0.92	GC, OTC	0.85
St_L	4	None, Fert	7.45**	4	—	Gymno	—	4	—	OTC	—

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

Light stress) there were significant Time and Func Grp effects but no significant differences among Stress categories (Table 3). Examination of these data revealed a small ($n=2$) group of long-duration studies (>365 days), both involving gymnosperms, whose belowground response was over twice that of the remaining 22 studies. Excluding those two studies (both from Johnson et al. 1994), which restricted Time to level 3 (100–365 days), resulted in a significant Stress Q_b but no other. That is, there were significant differences among Stress category means, but only after removal of the two outlier studies. While these two studies might well merit further examination (e.g., why were they outliers?), they were clearly distinct from the other 22 studies and obscured significant differences among Stress categories in that group. Below-ground biomass response to CO_2 was not significantly different from zero under fertility stress ($+10.6\%$, ns) and was not affected by low light or UVB stress relative to unstressed plants although low sample sizes renders this latter conclusion very tentative (Fig. 3).

Leaf biomass responses to CO_2 also showed significant Q_b for several categorical variables. Across the entire dataset, leaf biomass increased significantly under high CO_2 ($+31\%$, $k=50$) but the magnitude of this response depended on both interacting stresses and on functional group affiliation (Table 2). Studies with no interacting stress treatment ($k=37$) had no other significant Q_b (Table 3) and showed a mean stimulation of W_L under high CO_2 of 37.1% (Fig. 3). The remaining ten studies showed significant variation among Stress (Fert, UVB), Func Grp (Angiosperm, Gymnosperm), Pot (<0.5 – 9 l), and Method (GC, GH) levels. It was not possible to partition this variation completely since several categorical variables were confounded. For example, all four gymnosperm studies were conducted in growth chambers in pots <2.5 l. Stress treatments were not confounded with any other variable, however. Fertility stress reduced the W_L CO_2 response to zero while the magnitude of the CO_2 response under UVB stress was not significantly different from that of unstressed plants (Fig. 3). Stem biomass response to CO_2 showed a very similar pattern to W_B and W_L (Table 2, Fig. 3), with unstressed plants having a highly significant response ($+38.6\%$, $k=33$) but with low soil fertility reducing this growth stimulation to zero.

There was no evidence for significant Stress, Time, or Func Grp effects on A at high CO_2 (Table 2). Pot and Method did, however, show significant Q_b . For plants grown in GCs there was no Pot Q_b (Table 3) and an overall mean stimulation of A of 27.5% at high CO_2 (Fig. 4). For plants grown in GHs or OTCs and in pots >2.4 L, A was stimulated 54.3% under CO_2 enrichment (Table 3, Fig. 4), although there remained a significant Time Q_b for this group. The time effect was difficult to account for, with the level 3 mean (100–365 days) being greater than means from levels 1, 2, or 4 which were not different from one another (data not shown). Net CO_2 assimilation in GH or OTC plants grown in pots <2.5 l

was significantly less (19% , $k=9$) than in plants grown in larger pots or in the ground.

Elevated CO_2 stimulation of A in mature, open-grown *Pinus taeda* exposed to c. 55 Pa CO_2 for 2 years in a FACE experiment (Ellsworth et al. 1997) was 31% , outside the 95% CI of OTC and GH grown plants but very similar to the GC mean (Fig. 4). Part of the explanation for a reduced response relative to other 'field-grown' trees may be lower CO_2 levels used in this free-air CO_2 enrichment (FACE) study compared to most OTC experiments (c. 70 Pa). Photosynthetic acclimation could also be more severe than in non-FACE systems (see below). With a sample size of one it is impossible to test for a "FACE effect" *per se*, and additional data are of great importance in resolving differences in the CO_2 response, if any, between FACE-grown trees and those from the bulk of our other experimental systems.

Photosynthetic acclimation, calculated as the ratio of A in elevated compared to ambient grown plants both measured at elevated CO_2 , was affected overall only by pot size, with plants in small pots (<0.5 l), showing significant A_{accl} (-36% , $k=5$), while plants grown in larger pots showed no evidence for A_{accl} under any conditions (Tables 2, 3, Fig. 4). FACE-grown *Pinus taeda* showed A_{accl} of -16.5% , outside the 95% CI of other "large pot" studies. The likelihood of low water or nutrient supply contributing to the FACE A_{accl} response was low since Stress showed no significant Q_b in the overall data set. Increased sample size and estimates of among-FACE experiment variation clearly are needed to increase the power of these quantitative comparisons. Stomatal conductance showed a modest (-11%) but not statistically significant reduction in plants grown under high CO_2 while R_d (expressed on a leaf mass basis) was significantly reduced (-18%) (Fig. 4). Neither g_s nor R_d

Fig. 4 Gas exchange responses of trees to elevated CO_2 . Net CO_2 assimilation rate (A), acclimation to elevated CO_2 (A_{accl}), stomatal conductance (g_s) and leaf dark respiration (R_d) in plants grown under elevated compared to ambient CO_2 . Mean $\pm$ 95% confidence interval (k) (GH greenhouse, OTC field-based open-top chamber, FACE free-air CO_2 enrichment, GC growth chamber)

Fig. 5 Leaf nitrogen (N_L) and starch (St_L) content in elevated compared to ambient CO_2 grown plants. Both nitrogen and starch were reported on a tissue mass basis. Further subdivision of St_L studies was by angiosperm (*Angio*) vs. gymnosperm (*Gymno*) and no interacting stress (*None*) vs. low-fertility stress (*Fert*). Mean $\pm$ 95% confidence interval (k)

responses were affected by any categorical variable (Table 2).

Leaf nitrogen (mass basis) showed a highly significant reduction at high CO_2 (-16.4%, Fig. 5) and this response was unaffected by Stress level or other categorical variables (Table 2). Leaf starch response to elevated CO_2 was affected by Stress, Pot, and Func Grp (Table 2). In angiosperms, St_L increased 67.6% at high CO_2 , significantly more than in unstressed (+23.6%), or stressed (ns) gymnosperms (Fig. 5).

Discussion

Our meta-analysis of CO_2 responses in trees leads to a number of conclusions that we can state with considerable certainty, being based on many independent studies sharing numerous experimental design features. In particular, it is clear that both A and W_T increase significantly at twice ambient CO_2 , regardless of growth conditions. These results agree qualitatively with other reviews of this literature, but our quantitative summary of CO_2 effect sizes often differ significantly from earlier estimates. For example, our CO_2 effect size estimate of +31% for W_T under non-stressed, control conditions was less than half the CO_2 effect calculated by McGuire et al. (1995). In their review of 77 studies of elevated CO_2 involving N manipulations they found a 71% biomass increase in high CO_2 , higher N treatment trees compared to ambient CO_2 , higher N treatment trees. However, as their results were drawn only from studies involving soil N manipulations, the higher N and lowest N treatments could have provided greater soil N than the typical no-stress and low fertility treatments respectively in our analysis. Interestingly, the 50% relative reduction in the CO_2 growth response calculated by McGuire et al.

(1995) as due to low soil N availability (i.e., only a 35% growth enhancement in the lowest N treatments) was identical to our observation of a 50% reduction in CO_2 stimulation of W_T in nutrient-stressed plants (+16%). Eamus and Jarvis (1989) also estimated a significantly greater biomass response to elevated CO_2 (+40%) than we found, while Ceulemans and Mousseau (1994) distinguished between the CO_2 growth response of conifers (+38%) and broadleaved species (+68%), a division with no statistical basis in our dataset. Lastly, Wullschlegel et al. (1995) calculated virtually the same overall dry weight response to CO_2 in unstressed plants (+32%, $k=295$) as we did, but found no reduction in this response under low nutrient conditions (+30%, $k=82$).

These reviews differ from one another in many respects, including their overall objectives, their scope, and the collection of literature under consideration. It is difficult, therefore, to identify precisely the component(s) responsible for these differences in CO_2 effect size estimates. A contributing factor certainly must be basic differences in the authors' approach to quantitative research integration and the statistical tools (or lack thereof) that were used. To the extent that resolving differences of 2–3 fold in our estimates of CO_2 effects on tree growth is of importance (and we suggest it is) we must abandon ad hoc or ill-defined concepts for summarizing independent research results in favor of statistically robust meta-analytic methods. Only then will we be able to critically evaluate competing estimates of the likely magnitude of CO_2 stimulated tree growth on, for example, low nutrient soils, or the relative importance of taxonomic or functional group affiliation in the CO_2 response.

There has been considerable debate whether CO_2 enrichment results in shifts in root:shoot ratio (R/S) and, if so, under what conditions this occurs. Biomass allocation models such as functional balance (Davidson 1969) and carbon/nutrient substrate ratio (Reynolds and Thornley 1982) predict that as tissue C:N ratios rise and N becomes more limiting relative to C, biomass allocation to roots will increase. Thus, high CO_2 should elicit similar shifts in R/S as does low soil N. Evidence for such a CO_2 effect in trees has been equivocal, however. Eamus and Jarvis (1989) considered the bulk of the evidence to indicate an increase in R/S, particularly under low nutrient conditions, a conclusion supported by Ceulemans and Mousseau (1994). Norby (1994) observed that CO_2 effects on root allocation could easily be confounded with CO_2 effects on developmental rate and he estimated a modest (+6%) increase in R/S at high CO_2 , with no differential response under nutrient stress. Similarly, neither McGuire et al. (1995) nor Wullschlegel et al. (1995) found evidence for a significant CO_2 effect on biomass allocation under any conditions. We analyzed CO_2 effects on individual biomass components rather than R/S, which are rarely reported with error estimates, and found little evidence to support significant shifts in allocation, whether to leaves, stems, or

roots, under most environmental or cultural conditions. The only condition under which allocation might shift in favor of roots was nutrient stress, but this response was not statistically significant. It is interesting to note, however, that the CO_2 effect on W_T under nutrient stress although reduced was still significant and the only biomass component with a similar mean CO_2 effect size under nutrient stress was W_B . This observation lends qualified support to predictions of increased R/S at high CO_2 under low soil nutrient availability but additional data clearly will be needed to resolve this important issue.

There is broad agreement among reviewers on the overall magnitude of tree photosynthetic responses to CO_2 enrichment, although less so on factors affecting that response. Estimates of overall CO_2 effects on A range from +44% (Gunderson and Wullschlegel 1994) to +54% (this study). Low soil nutrients have often been considered of primary importance in reducing the magnitude of this response (e.g., McGuire et al. 1995; Curtis 1996) but rarely have the relative effects of other environmental factors been compared quantitatively to that of soil nutrients. We found significant Pot and Method Q_b across all 79 studies in our database but no significant differences among stress categories. However, of 50 GH and OTC studies that were conducted in large pots or in the ground, only 7 involved low nutrient treatments, a small sample conveying relatively little statistical power. While our failure to detect significant nutrient effects may be due to sampling error, this example illustrates a general concern that must be confronted by quantitative reviewers of the literature on the effects of elevated CO_2 . That is, all identifiable sources of variation in a dataset must be examined before summary statistics are calculated and conclusions drawn. If this is not done, variation due to one factor (e.g., pot size) may be confounded with that of another (e.g., soil nutrients), leading to inaccurate or erroneous conclusions regarding the importance of either factor. This is particularly true for studies with elevated CO_2 where cultural conditions are known to affect the magnitude of the treatment response (Thomas and Strain 1991; McConnaughay et al. 1993; Kennedy 1995). Our results clearly show that environmental stress is of less importance than certain cultural factors in altering the magnitude of photosynthetic responses to high CO_2 and that significant, sustained increases in A can be expected in trees as atmospheric CO_2 levels rise.

Photosynthetic acclimation, or down-regulation, represents a suite of physiological processes which cause photosynthetic capacity in plants grown under high CO_2 to decline relative to plants grown under ambient CO_2 (Stitt 1991). To evaluate the magnitude of A_{accl} in trees grown under high CO_2 we adopted the convention suggested by Gunderson and Wullschlegel (1994) of comparing A in plants grown under elevated and ambient CO_2 measured at a common CO_2 level (either internal or external to the leaf). Our results show no consistent evidence for A_{accl} (-1%, ns), except in trees grown in pots <0.5 l (-36%, $P < 0.01$). This is in

contrast to both the prevailing view based on narrative reviews (Ceulemans and Mousseau 1994; McGuire et al. 1995) and the overall 21% acclimation response across 20 studies reported by Gunderson and Wullschlegel (1994). The 24 "larger pot" studies remaining in our dataset were almost evenly divided among those showing strong A_{accl} (e.g., Johnsen 1993; Curtis et al. 1995), no A_{accl} (e.g., Downton et al. 1990; Grulke et al. 1993), and significant up-regulation (e.g., Kaushal et al. 1989; Sharkey et al. 1991). Given the heterogeneity of this group, and the small number of studies with common stress treatments, we suggest it is premature to conclude that photosynthetic acclimation is a universal response by trees to growth under high CO_2 under any particular set of conditions. Additional results from forest FACE experiments could help define those conditions but within and among-study variance estimates will be required for any rigorous statistical tests to be made.

Interpreting the effects of elevated CO_2 on tree g_s presents similar problems to those raised regarding A_{accl} . Reviewers of data on g_s responses, including measurements from herbaceous species, generally suggest a significant reduction in g_s to be the norm, with the well documented sensitivity of stomata to internal CO_2 level (Farquhar and Sharkey 1982) offered as a plausible response mechanism. Acclimation of g_s to high CO_2 is a possibility, however, and while no physiological mechanism for acclimation has been proposed, one result of acclimation could be a change in stomatal sensitivity to CO_2 (Sage 1994). Eamus and Jarvis (1989) estimated a reduction of from -10% to -60% in g_s of trees grown under elevated compared to ambient CO_2 but acknowledged numerous exceptions. We found considerable variation in the magnitude of CO_2 effects on g_s as well. Although the overall mean response across 48 studies was a modest -11%, this effect was not statistically different from zero, nor were there significant stress or cultural modifiers to this response. As with the distribution of A_{accl} values, our g_s dataset contained numerous studies reporting strongly negative (e.g., Bassow et al. 1994; Eamus et al. 1995), not statistically significant (e.g., Hollinger 1987; Bunce 1992), and strongly positive (e.g., Norby and O'Neill 1991; Pettersson and McDonald 1992) effects of high CO_2 on g_s . Additional data will be required before we can state with certainty either the magnitude or the direction of CO_2 effects on tree g_s .

In contrast to the uncertainty regarding CO_2 effects on A_{accl} and g_s , our analysis provides strong support and robust summary statistics for the widely accepted view (e.g., Amthor 1994; Wullschlegel et al. 1994) that growth at elevated CO_2 results in significant reductions in R_d and N_L when both are expressed on a tissue mass basis. Working with a similar, though somewhat smaller dataset, Curtis (1996) found reduced N_L when reported on a leaf mass but not when reported on a leaf area basis, suggesting that in most circumstances the mass-based N reduction under CO_2 enrichment was due to increased leaf density rather than N reallocation. In the

present study we documented large increases in St_L under all conditions except in nutrient stressed gymnosperms. Given the strong positive relationship between tissue N content and both photosynthesis (Field and Mooney 1986) and maintenance respiration (Ryan 1991) it is important to determine when growth at high CO_2 leads to a net decrease in non-storage leaf N content as opposed to reduced leaf N concentration due to changes in specific leaf area. The extent to which CO_2 enrichment leads to functional decreases in N_L could be an important determinant of long-term growth and allocational responses to elevated CO_2 (Luo et al. 1994). It is also important to determine whether reduced N_L of green leaves carries over into an increased C:N ratio of naturally senesced leaf litter. Although evidence that elevated CO_2 alters leaf decomposition rates is at present equivocal (O'Neill and Norby 1996), reduced N mineralization from soil organic matter could provide a potent negative feedback on long-term forest productivity with rising CO_2 (Zak et al. 1993).

It is important to note that no single meta-analysis is likely to be definitive, and that multiple approaches and perspectives should be encouraged. For example, while our conclusions regarding CO_2 effects on A , A_{accl} , and g_s are in broad agreement with those of Curtis (1996), the differences in effect size metric (lr vs. d -index) and in the strategies for partitioning within and between group variance in the two meta-analyses resulted in several qualitatively different outcomes. The most important was for A_{accl} , where Curtis (1996, Fig. 3a) found a highly significant (although numerically modest) overall CO_2 effect, while in the present study we found no CO_2 effect in non-FACE studies (Fig. 4). However, the overall mean effect size estimate in Curtis (1996) included the responses of plants grown in small pots (<0.5 l) which were shown in both studies to have significantly greater A_{accl} than plants grown in larger pots. Here, these plants were excluded from the overall analysis, leading to the result of no significant A_{accl} . In addition, where the number of studies within a category is small, as was the case in numerous instances here, it is particularly important to repeat the meta-analysis as new data becomes available.

In conclusion, quantitative integration of the elevated CO_2 literature has been hampered by inappropriate sampling and statistical methods, leading to uncertainty in the magnitude of CO_2 effects on fundamental processes controlling carbon gain in woody vegetation and of the importance of environmental factors in altering the magnitude of these effects. Statistically defensible methods of integrating diverse research results have been developed over the past 50 years and are now firmly in place in the medical and social sciences (Mann 1990). Meta-analysis is not a substitute for well designed, multi-factorial experiments and it is important to acknowledge the limits to establishing causal relationships from meta-analytic results where categorical groups created by the meta-analyst were not randomly assigned treatments within the primary studies (Miller and Pol-

lock 1994). What meta-analysis does offer is an objective and statistically rigorous methodology for integrating primary research results with the goal of estimating the magnitude of treatment effects within and among categorical groups. We suggest that it is important from a scientific as well as a policy perspective that elevated CO_2 research results continue to be integrated using these tools.

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Appendix 2 The species, environmental stress factors in addition to CO₂ (Stress), variables measured, and citation for all studies used in the meta-analysis. The variables measured were: total above- + below-ground biomass (W_T), below-ground biomass (W_B), stem biomass (W_S), total leaf biomass (W_L), light saturated net CO₂ assimilation (A), photosynthetic acclimation or downregulation (A_{accl}), stomatal conductance (g_s), leaf dark respiration (R_d , expressed on a leaf mass basis), leaf nitrogen concentration (N_L , expressed on a mass basis), and leaf starch concentration (St_L ,

expressed on a mass basis). The entire database, containing nearly 800 observations (at the time of this writing), is available for public use from the Carbon Dioxide Information and Analysis Center (CDIAC, Oak Ridge National Laboratory). Files may be obtained by anonymous FTP at address: cdiac.esd.ornl.gov, directory pub/db1018. Access codes and other important information are viewable in the readme file. The database can also be accessed via CDIAC's homepage: <http://cdiac.esd.ornl.gov>, under Products and Services, Anonymous FTP Service, FTP area, db1018.

Species	Stress	W_T	W_L	W_S	W_B	A	A_{accl}	g_s	R_d	N_L	St_L	Citation
<i>Acacia mangium</i>	None					*						Ziska et al. (1991)
<i>Acer pensylvanicum</i>	Fert		*	*				*				Bassow et al. (1994)
<i>Acer pensylvanicum</i>	Fert				*							Bassow et al. (1994)
<i>Acer pensylvanicum</i>	Fert/light				*							Bazzaz and Miao (1993)
<i>Acer pensylvanicum</i>	Fert/light	*										Bazzaz and Miao (1993)
<i>Acer pensylvanicum</i>	Fert/light	*										Bazzaz et al. (1993)
<i>Acer rubrum</i>	Fert/light				*							Bazzaz and Miao (1993)
<i>Acer rubrum</i>	Fert/light	*										Bazzaz and Miao (1993)
<i>Acer rubrum</i>	Fert/light	*										Bazzaz et al. (1993)
<i>Acer rubrum</i>	None	*										Bunce (1992)
<i>Acer rubrum</i>	Light					*		*		*		Kubiske and Pregitzer (1996)
<i>Acer saccharinum</i>	None	*				*		*				Bunce (1992)
<i>Acer saccharum</i>	None	*	*							*	*	Lindroth et al. (1993)
<i>Acer saccharum</i>	Temp					*		*				Norby et al. (1996)
<i>Acer saccharum</i>	None									*		Reid and Strain (1994)
<i>Acer saccharum</i>	None					*						Reid and Strain (1994)

Appendix 2 (continued)

Species	Stress	W_T	W_L	W_S	W_B	A	A_{acc}	g_s	R_d	N_L	St_L	Citation
<i>Alnus glutinosa</i>	None					*		*	*	*		Vogel and Curtis (1995)
<i>Alnus rubra</i>	Fert	*	*	*	*	*				*		Amone and Gordon (1990)
<i>Betula alleghaniensis</i>	Fert		*	*	*			*				Bassow et al. (1994)
<i>Betula alleghaniensis</i>	Fert/light	*			*							Bazzaz and Miao (1993)
<i>Betula alleghaniensis</i>	Fert/light	*			*							Bazzaz et al. (1993)
<i>Betula alleghaniensis</i>	None	*		*	*					*		Rocheffort and Bazzaz (1992)
<i>Betula lenta</i>	None	*	*	*	*					*		Rocheffort and Bazzaz (1992)
<i>Betula papyrifera</i>	Light					*		*		*		Kubiske and Pregitzer (1994)
<i>Betula papyrifera</i>	None	*	*	*	*					*		Rocheffort and Bazzaz (1992)
<i>Betula papyrifera</i>	None									*	*	Roth and Lindroth (1994)
<i>Betula pendula</i>	Temp	*				*	*		*			Mortensen (1994)
<i>Betula pendula</i>	None	*				*		*		*	*	Pettersson and McDonald (1992)
<i>Betula pendula</i>	Fert									*	*	Pettersson et al. (1993)
<i>Betula populifolia</i>	Fert		*	*	*			*				Bassow et al. (1994)
<i>Betula populifolia</i>	Fert/light	*			*							Bazzaz and Miao (1993)
<i>Betula populifolia</i>	Fert/light	*			*							Bazzaz et al. (1993)
<i>Betula populifolia</i>	None	*	*	*	*					*		Rocheffort and Bazzaz (1992)
<i>Betula pubescens</i>	O ₃ /temp	*	*	*	*							Mortensen (1995)
<i>Brachychiton populneum</i>	None					*						Idso and Kimball (1993)
<i>Castanea sativa</i>	None	*		*								Couteaux et al. (1992)
<i>Castanea sativa</i>	None								*			El Kohen et al. (1991)
<i>Castanea sativa</i>	Fert	*	*	*	*					*		El Kohen et al. (1992)
<i>Castanea sativa</i>	None	*	*	*	*	*						El Kohen et al. (1993)
<i>Castanea sativa</i>	None	*	*	*	*	*			*			Mousseau (1993)
<i>Castanea sativa</i>	None	*		*	*							Mousseau and Enoch (1989)
<i>Cecropia obtusifolia</i>	None/comp	*				*		*				Reekie and Bazzaz (1989)
<i>Cedrus atlantica</i>	None					*	*	*			*	Kaushal et al. (1989)
<i>Citrus aurantium</i>	None		*	*	*							Ferguson et al. (1986)
<i>Citrus aurantium</i>	None					*						Idso et al. (1991)
<i>Citrus sinensis</i>	None	*	*	*	*	*	*					Downton et al. (1987)
<i>Eucalyptus microtheca</i>	None					*						Idso and Kimball (1993)
<i>Eucalyptus</i>	None					*						Idso and Kimball (1993)
<i>polyanthemus</i>												
<i>Eucalyptus tetradonta</i>	None					*						Eamus et al. (1995a)
<i>Fagus grandifolia</i>	None					*				*		Reid and Strain (1994)
<i>Fagus sylvatica</i>	None					*						El Kohen et al. (1993)
<i>Fagus sylvatica</i>	None					*	*					Jarvis et al. (1994)
<i>Ficus obtusifolia</i>	None					*						Ziska et al. (1991)
<i>Fraxinus americana</i>	Fert/light	*			*							Bazzaz and Miao (1993)
<i>Fraxinus americana</i>	Fert/light	*			*							Bazzaz et al. (1993)
<i>Garcinia mangostana</i>	None		*	*	*	*	*					Downton et al. (1990)
<i>Gliricidia sepium</i>	Fert									*		Thomas et al. (1991)
<i>Lindera benzoin</i>	None									*		Cipollini et al. (1993)
<i>Liquidambar styraciflua</i>	None					*	*	*				Fetcher et al. (1988)
<i>Liriodendron tulipifera</i>	None					*		*	*	*		Wullschlegel et al. (1992a)
<i>Liriodendron tulipifera</i>	None					*		*		*		Gunderson et al. (1993)
<i>Liriodendron tulipifera</i>	Fert	*	*	*	*	*		*		*		Norby and O'Neill (1991)
<i>Liriodendron tulipifera</i>	None		*	*		*		*	*			Norby et al. (1992)
<i>Liriodendron tulipifera</i>	None					*		*	*		*	Wullschlegel et al. (1992b)
<i>Malus domestica</i>	None	*				*		*				Bunce (1992)
<i>Maranthus corymbosa</i>	None	*	*	*	*							Berryman et al. (1993)
<i>Maranthus corymbosa</i>	None					*	*	*				Eamus et al. (1993)
<i>Maranthus corymbosa</i>	None					*		*				Eamus et al. (1995b)
<i>Myriocarpa longipes</i>	None/comp	*				*		*				Reekie and Bazzaz (1989)
<i>Nothofagus fusca</i>	None	*				*	*	*				Hollinger (1987)
<i>Picea abies</i>	None					*	*					Marek et al. (1995)
<i>Picea abies</i>	Temp	*				*	*		*			Mortensen (1994)
<i>Picea abies</i>	O ₃	*										Polle et al. (1993)
<i>Picea glauca</i>	UVB	*	*	*	*							Yakimchuk and Hoddinott (1994)
<i>Picea mariana</i>	Fert/H ₂ O	*				*	*	*				Johnsen (1993)
<i>Picea mariana</i>	UVB	*	*	*	*							Yakimchuk and Hoddinott (1994)
<i>Pinus banksiana</i>	UVB	*										Stewart and Hoddinott (1993)
<i>Pinus banksiana</i>	UVB	*	*	*	*							Yakimchuk and Hoddinott (1994)

Appendix 2 (continued)

Species	Stress	W_T	W_L	W_S	W_B	A	A_{acc}	g_s	R_d	N_L	St_L	Citation
<i>Pinus echinata</i>	None	*		*								Norby et al. (1987)
<i>Pinus echinata</i>	None	*	*	*	*							O'Neill et al. (1987)
<i>Pinus eldarica</i>	None		*									Garcia et al. (1994)
<i>Pinus nigra</i>	None					*	*	*			*	Kaushal et al. (1989)
<i>Pinus ponderosa</i>	Temp	*							*			Callaway et al. (1994)
<i>Pinus ponderosa</i>	None		*			*	*	*		*		Gruke et al. (1993)
<i>Pinus ponderosa</i>	Fert				*							Johnson et al. (1994)
<i>Pinus ponderosa</i>	None							*				Surano et al. (1986)
<i>Pinus radiata</i>	Fert							*				Conroy et al. (1988)
<i>Pinus radiata</i>	None	*				*	*	*				Hollinger (1987)
<i>Pinus strobus</i>	None									*	*	Roth and Lindroth (1994)
<i>Pinus sylvestris</i>	Temp					*	*		*			Wang et al. (1995)
<i>Pinus taeda</i>	None					*	*	*				Fetcher et al. (1988)
<i>Pinus taeda</i>	Fert									*		Lewis et al. (1994)
<i>Pinus taeda</i>	None					*	*	*				Liu and Teskey (1995)
<i>Pinus taeda</i>	None		*	*	*							Sullivan and Teramura (1994)
<i>Pinus taeda</i>	None					*						Teskey (1995)
<i>Pinus taeda</i>	Fert					*					*	Tissue et al. (1993)
<i>Pinus taeda</i>	H ₂ O		*	*	*							Tschaplinski et al. (1993)
<i>Pinus taeda</i>	None		*							*	*	Williams et al. (1994)
<i>Pinus taeda</i>	None					*	*					Ellsworth et al. (1997)
<i>Piper auritum</i>	None/comp	*				*		*				Reekie and Bazzaz (1989)
<i>Populus euramericana</i>	None					*		*				Gaudillere and Mousseau (1989)
<i>Populus euramericana</i>	Fert	*	*	*	*					*		Pregitzer et al. (1995)
<i>Populus grandidentata</i>	None			*	*	*	*	*		*		Curtis and Teeri (1992)
<i>Populus grandidentata</i>	None					*	*	*				Curtis et al. (1994)
<i>Populus interamericana</i>	None					*						Lemeur et al. (1992)
<i>Populus tremuloides</i>	Fert									*		Brown (1991)
<i>Populus tremuloides</i>	None	*	*							*	*	Lindroth et al. (1993)
<i>Populus tremuloides</i>	None					*	*					Sharkey et al. (1991)
<i>Populus euramericana</i>	Fert	*				*	*		*	*	*	Curtis et al. (1995)
<i>Pseudotsuga menziesii</i>	None		*		*							Gorissen et al. (1995)
<i>Pseudotsuga menziesii</i>	None	*				*	*	*				Hollinger (1987)
<i>Quercus alba</i>	None					*		*				Gunderson et al. (1993)
<i>Quercus alba</i>	Fert		*	*	*	*						Norby and O'Neill (1989)
<i>Quercus alba</i>	None		*	*						*		Norby et al. (1986)
<i>Quercus alba</i>	None	*	*	*								O'Neill et al. (1987)
<i>Quercus alba</i>	None					*	*					Sharkey et al. (1991)
<i>Quercus alba</i>	None								*			Wullschleger and Norby (1992)
<i>Quercus alba</i>	None					*		*	*		*	Wullschleger et al. (1992a)
<i>Quercus alba</i>	None								*			Wullschleger et al. (1995)
<i>Quercus prinus</i>	None	*				*		*				Bunce (1992)
<i>Quercus robur</i>	None					*		*				Bunce (1992)
<i>Quercus rubra</i>	Fert/light	*			*							Bazzaz and Miao (1993)
<i>Quercus rubra</i>	Fert/light	*										Bazzaz et al. (1993)
<i>Quercus rubra</i>	Light					*				*		Kubiske and Pregitzer (1996)
<i>Quercus rubra</i>	None	*	*							*	*	Lindroth et al. (1993)
<i>Senna multijuga</i>	None/comp	*				*		*				Reekie and Bazzaz (1989)
<i>Tabebuia rosea</i>	None					*						Ziska et al. (1991)
<i>Trichospermum mexicanum</i>	None/comp	*				*		*				Reekie and Bazzaz (1989)

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