Analysis of Aspen FACE Phenological, Morphometric and Growth Data for 1998-2000

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1. Introduction

Ecophys is a complex computer model that simulates the growth of hybrid poplar and aspen trees. The name Ecophys has been around for over a decade. However, the simulation's capabilities and submodels of various processes change yearly. The simulation discussed in this paper would be more accurately called Ecophys-2002. Though Ecophys continues to evolve, its primary purposes are still to identify major physiologically-based factors that influence the growth of trees and to predict how interactions among them will affect growth (Host et al., 1990; Rauscher et al., 1990).

This report concerns the current Ecophys simulation of the growth of aspen clone 259 given the environmental conditions of the Free-Air CO_2 and O_3 Enrichment (Aspen FACE) site in Rhinelander, Wisconsin (http://www.nrri.umn.edu/factsii). This work is preliminary to similar investigations of the growth of other aspen clones at the Aspen FACE site as well as patch-level simulations including competition among clones.

The Aspen FACE site was established in 1997 in order for researchers to study the growth of five different aspen clones, as well as maple and birch trees in the presence of elevated levels of carbon dioxide (CO_2) and ozone (O_3) gases. The main objective of the Aspen FACE experiment is to examine, for predictive purposes, the effects of elevated CO_2 and O_3 on ecological interactions of northern hardwood forests (Dickson et al., 2000). There are twelve rings at the site containing 584 trees. Three of the rings are treated with elevated CO_2, three are treated with elevated O_3, three are treated with both elevated CO_2 and O_3, and three have ambient levels of CO_2 and O_3 (the control rings).

This report details Ecophys simulation results of the growth of a juvenile aspen tree, clone 259, using field measurement data received from Aspen FACE site investigators for the years 1998 through 2000. Warren Heilman, (2002), and Jaak Sober, (2002), provided the Aspen FACE environmental data. Mariah Olson, (2002), analyzed and completed these data sets, and converted them to hourly input files for Ecophys. Jud Isebrands, environmental forestry consultant and former member of the Aspen FACE steering committee, and Mark Kubiske and Evan McDonald of the North Central Forest Experimental Station contributed their expertise concerning aspen growth response to CO_2 and O_3 and the Aspen FACE experiment (see Appendix A).

Kyle Roskoski, under the direction and advisement of K. Lenz, H. Stech, and G. Host, carried out the research described in this report, as well as requisite computer programming. He generated all of the figures and tables that appear in this report. See also the report K. Roskoski, (2002).

Figure 1 shows a sample screen shot of an Ecophys simulation in the second year of growth.

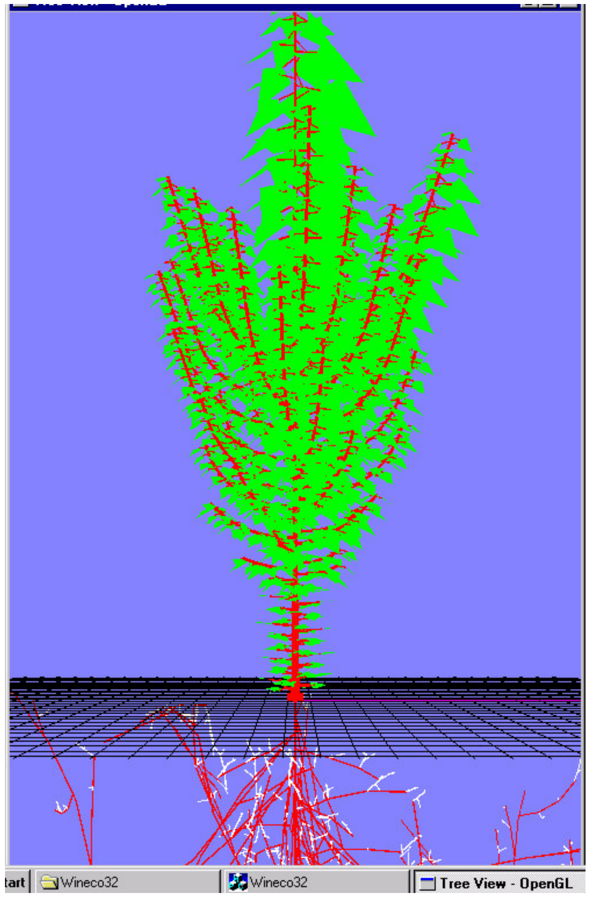


Figure 1 A second-year ECOPHYS tree

In addition to hourly environmental data, Ecophys requires a variety of clonal parameters as inputs. Some of the parameter values can be estimated directly from field measurements, including specific gravity, bud-break and bud-set dates, and end-of-season leaf senescence start date and rate. Others such as leaf initiation rate, and leaf, branch and bud death submodel parameters, are estimated indirectly.

2. Data sets

FACE site weather data was received from Warren Heilman, (2002) and Jaak Sober, (2002), for the years 1998, 1999, and 2000. The subset of this environmental data used for Ecophys simulation includes hourly averages of temperature, light intensity, relative humidity, and CO_2 and O_3 gas levels. Phenological and growth data from the Aspen FACE site was received from Jud Isebrands and Evan McDonald, (2002). It is organized according to aspen clone and treatment. The phenological data includes bud-break, bud-set and end-of-season leaf senescence dates for 1999 and 2000. The growth data includes stem height and stem diameter measurements for 1998 and 2000, and leaf area measurements for 2000. Stem height and stem diameter modified averages for 1999 were obtained from Isebrands et al., (2001).

In general, the methods of analysis of data vary according to data type and depend upon several factors including the design of the experiment, the methods for data collection, the precision of measurements, time and spatial scales of data, redundancy or scarcity of measurements, and what information is sought from the data. For example, as noted in Dickson et al., (2000), when trees within treatment combinations are selected for measurement of physiological characteristics, it is important to know whether the same trees are measured each time or each measurement is made on a different random sample of individuals within plots. In the Aspen FACE experiment, in any given year the same trees were sampled for bud-set date as for bud abscission. For example, in ring 1.1, tree L19 was used to measure abscission and bud-set date. However, the trees sampled varied from year to year. For example, the clone 259 tree measured for bud-set date in ring 1.1 was not the same clone 259 tree measured for bud-set date in ring 1.1 in 1999. However, in ring 1.2, the same clone 259 tree was measured both years. In instances where the tree used for measurements changed from one year to the next, it may be that the original tree died or was severely damaged between seasons. Across the rings, for aspen 259, five trees measured were the same individuals in 2000 as in 1999, while seven individual trees were different in 2000 compared to 1999.

3. Analysis of Data

3.1 Bud-break and Bud-set Dates

Phenological data collected at the Aspen FACE site in 1999 and 2000 was used to estimate bud-break date and bud-set date parameters for Ecophys (see Table B.1 in Appendix B). The data for 1999 indicated May 17 as the bud-break date for each sample of clone 259 from each treatment. In the year 2000, bud-break dates varied from May 10 to May 12 with May 12 as the median date. As preliminary sensitivity analysis, Ecophys output for two years when May 8 was specified as the bud-break date was compared to that resulting when May 17 was specified as the bud-break date, using Aspen FACE 1998 weather data for both years. Figures 2 gives a preliminary indication of the sensitivity of Ecophys to the bud-break date according to its impact on the height growth of a simulated two-year tree. Note that Julian day one is January 1, 2000 and the rest of the days for the year are incremented through December 31, 2001. With all else kept the same, an earlier bud-break date in Ecophys results in a taller tree and a larger trunk diameter, which is to be expected since an earlier bud-break date results in a longer growing season. This 8-day increase in the length of each growing season lead to a 30% increase in Ecophys height growth after two years.

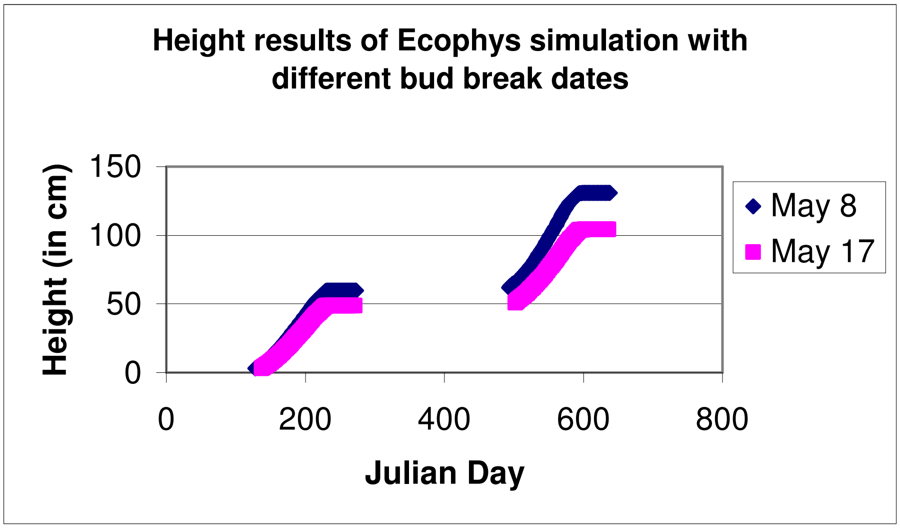


Figure 2

We found that, in contrast to bud-break date, the bud-set date was not the same across treatments. Table 3a shows the bud-set dates in 1999 recorded for aspen 259. For simulation purposes, we chose the median value recorded for each treatment as the bud-set date for that treatment in 1999. These dates were August 18 for the Control, September 3 for the CO_2 rings, August 13 for the O_3, and August 3 for the Cozone (CO_2 and O_3) rings.

1999 Bud-Set Dates for Aspen 259			
Control	CO2	O3	CO2+O3
7/15	8/18	7/15	8/3
8/18	9/3	8/13	8/3
8/26	9/3	8/18	8/3

Table 3a

Bud-set dates were also given for the 2000-growing season. These dates, in contrast to those in 1999, were much later and occurred after senescence had already begun (Table 3b).

2000 Bud-Set Dates for Aspen 259			
Control	CO2	O3	CO2+O3
9/15	9/15	9/15	9/15
9/15	9/15	9/15	9/15
9/18	9/18	9/18	9/18

Table 3b

Ecophys currently requires that the bud-set date is earlier than the leaf senescence date. Bug infestations and weather conditions may have caused the relationship between bud-set and senescence dates exhibited in the 2000 data.

3.2 The Start Date and Rate of Fall Leaf Senescence

Ecophys requires a start date and a rate of leaf drop for end-of-season leaf senescence. These parameters are estimated from leaf-senescence field data. Recording of senescence data for 1999 and 2000 at the Aspen FACE site began after senescence was already underway. Thus start dates and senescence rates were estimated from a linear least-squares fit to the 1999 and 2000 data. This report focuses on the 1999 senescence data. Since there was no senescence data for the 1998 season, the 1999 data was used for Ecophys simulation of senescence in 1998 as well as in 1999.

There were twelve trees sampled for senescence at the end of the year, one from each ring at the Aspen FACE site. The senescence field data for 1999, recorded weekly, for the O_3 rings are shown in Figure 4a, and for the Cozone rings in Figure 4b. The graphs indicate estimates for how far each sampled tree was into senescence on the date the data were recorded. Note that the percentage of leaves dropped by September 5 in the O_3 rings data varies from ten to almost sixty, while the Cozone data suggests a more uniform start for senescence. This could be indicative of increased stress on the trees in the O_3 rings. Alternatively, it could be that the data from ring 2.3 is atypical. In this study the data were assumed to be representative.

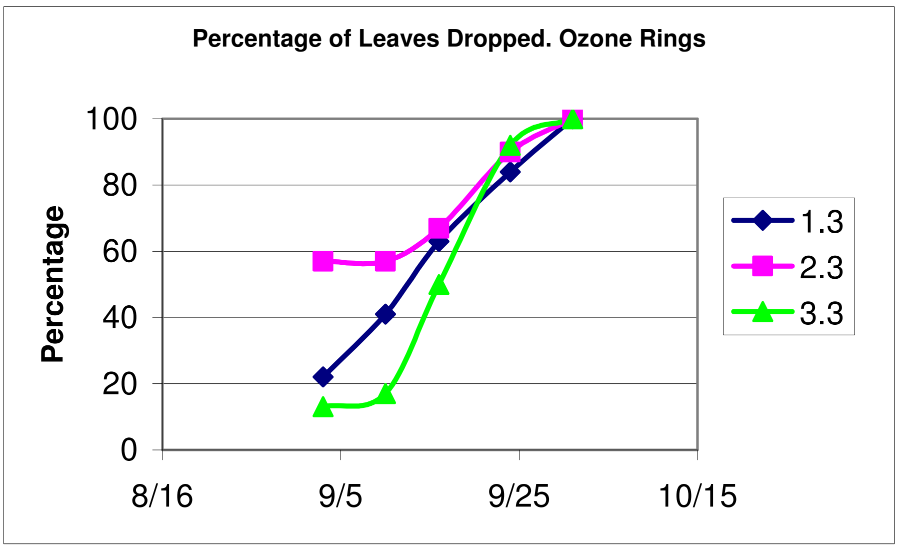


Figure 4a

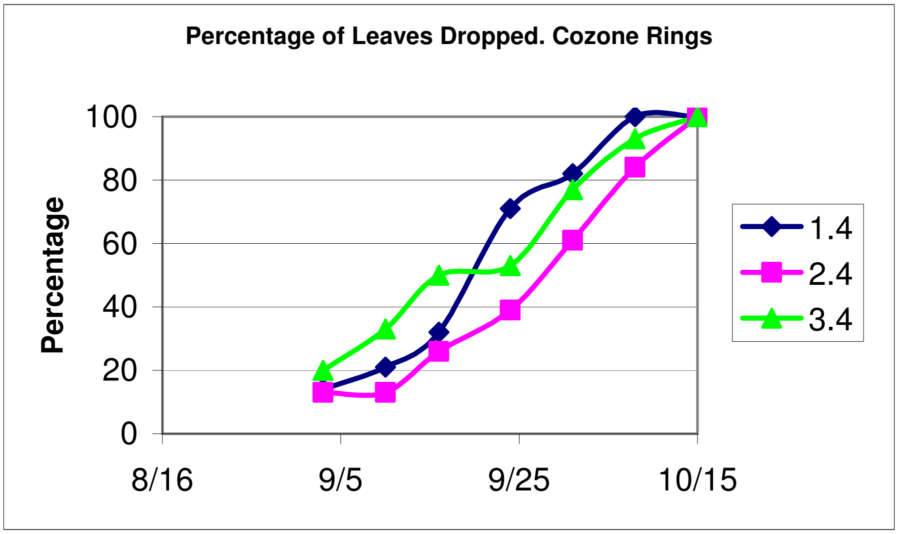


Figure 4b

Table 5 shows a sample of the senescence data collected at the Aspen FACE site. The percentage of leaves that had dropped by a given date was recorded. The top row of the table lists the dates that data were recorded, and the left column lists what ring each sample tree was in. Note that the data are listed for control rings first, followed by CO_2 rings, then O_3 rings, and finally Cozone rings. The numbers in the white rows are recorded data. In each orange row the numbers result from a linear least squares fit to the data in the white row immediately above it. Data indicating 100% or 0% were not used.

The linear least squares lines were computed using Excel spread sheet software. Each orange row lists an estimate for the senescence start date. Each entry in the column titled "Rate" is a calculated least squares linear rate of senescence when time is measured in weeks. Observe that the data show that the CO_2 sample trees were late to begin senescence, but finished at about the same time as the trees in the control rings. The rate column also indicates that the rate of senescence was higher in CO_2 rings.

					Leaf Senescence Dates of 1999 Current Terminal Data											
					Estimating start dates of senescence using a least squares linear fit											
Ring	Rate	30-Jul	6-Aug	13-Aug	20-Aug	27-Aug	3-Sep	10-Sep	16-Sep	24-Sep	1-Oct	8-Oct	12-Oct	15-Oct	19-Oct	22-Oct
1.1	12						27	27	36	55	73	100				
					0	7	19	31	43	55	67	79	86	92	100	
2.1	17						13	13	26	43	71	89	96	100		
							0	17	33	50	66	83	93	100		
3.1	25						0	0	0	14	39	57	81	87	100	
									0	14	39	63	77	88	100	
1.2	36						0	0	0	0	25	44	81	94	100	
										0	26	61	82	97	100	
2.2	31						0	0	0	14	27	59	97	100		
									0	4	36	67	85	98	100	
3.2	48						0	0	0	0	15	42	94	100		
										0	34	82	100			
1.3	21						22	41	63	84	100					
						0	21	42	63	84	100					
2.3	11						57	57	67	90	100					
		0	5	16	27	38	50	61	72	83	94	100				
3.3	28						13	17	50	92	100					
							0	28	55	83	100					
1.4	18						0	14	21	32	71	82	100			
							0	8	26	45	63	81	92	100		
2.4	15						13	13	26	39	61	84	100			
						0	2	17	31	46	61	75	83	90	98	100
3.4	14						20	33	50	53	77	93	100			
					0	4	18	32	47	61	75	89	97	103	100	

Table 5

The linear fits to the data from rings 2.1, 1.2, 1.3, and 2.4 were used for Ecophys simulation of fall senescence for each of the four treatments. The data for these rings were the median values within each treatment for most of the measurement dates. The equations for percentage of leaves dropped as a function of Julian day are as follows.

Control: $y = 2.37t - 583.02$

Rate of leaf drop is 2.37 % each day starting at $t = 246$ (Sept 4)

CO_2: $y = 5.12t - 1377.28$

Rate of leaf drop is 5.12 % each day starting at $t = 269$ (Sept 27)

O_3: $y = 3.01t - 719.39$

Rate of leaf drop is 3.01 % each day starting at $t = 239$ (Aug 29)

Cozone: $y = 2.09t - 512.05$

Rate of leaf drop is 2.09 % each day starting at $t = 245$ (Sept 3)

The number of leaves that have dropped by day t is the nearest integer to the product of y and the total number of leaves on the start date. Similar results were obtained for least squares lines for combined data from all three sampled trees within each treatment.

The number of leaves dropping per week in the field is useful for comparison with Ecophys output. To estimate the number of leaves dropped each week for each sampled tree, the assumption was made that the data titled “total lvs” gives the number of leaves per tree just prior to end-of-season senescence.

3.3 Leaf Initiation Rate

The rate at which new leaves emerge during the growing season prior to bud set is referred to as leaf initiation rate. Currently, Ecophys reads as input a fixed leaf initiation rate in hours. Varying the leaf initiation rate parameter affects the total number of leaves, total leaf area, the lengths and diameters of the internodes, and the branch architecture of the simulated tree. As the leaf initiation rate for Ecophys is increased, the lengths of the internodes increase and the total number of leaves decreases. The graphs in Figure 6 show how varying leaf initiation rate from 37 hours/leaf to 86 hours/leaf affects the total leaf area, the number of leaves, the trunk diameter, the tree height, and the total root length for a first-year simulation.

In the first five graphs the x-axis represents the Julian day. In the sixth graph the x-axis is the internode number from the base of the trunk up to the tip and the y-axis is the length of the internode in centimeters.

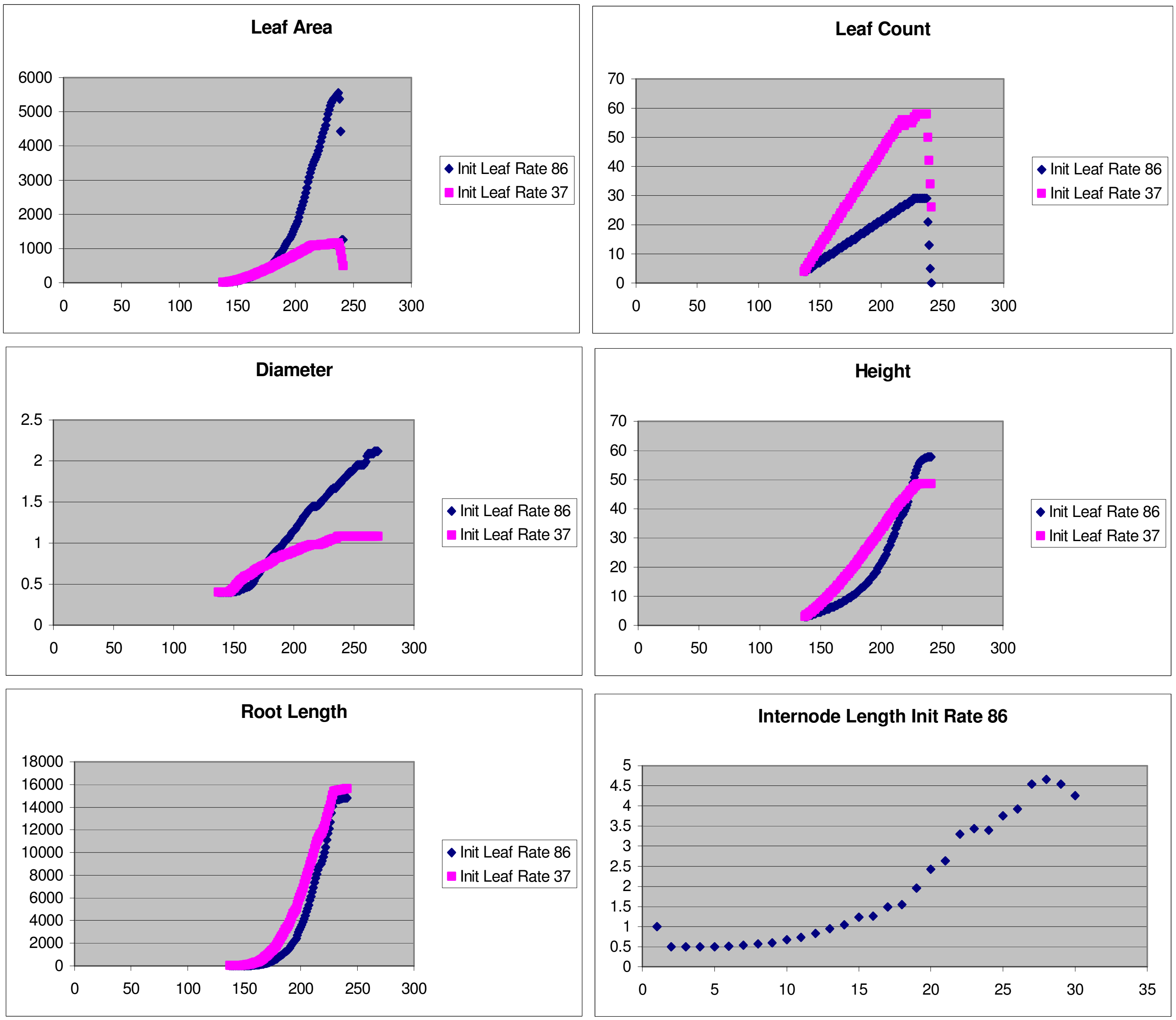


Figure 6

Measurements of internode lengths were taken by Kyle Roskoski at the Aspen FACE site in April, 2002 (see Table B.2 in Appendix B) . Internode lengths for aspen 259 were found to typically be 2-3 cm. With a leaf initiation rate of 37 hours, unrealistic internode lengths of typically less than 1 cm. were observed in Ecophys simulations with control-ring field conditions.

Leaf initiation rate is not the only variable in Ecophys affecting internode length. Calculations for the conversion of intercepted light to photosynthate, distribution of photosynthate to internodes, and conversion of photosynthate to internode biomass all affect internode length. Additional aspects of the simulation also affect internode length, including architectural parameters, the age at which an internode's growth switches from growth in length to growth in diameter, and the modeling of in-season leaf death, bud and branch death.

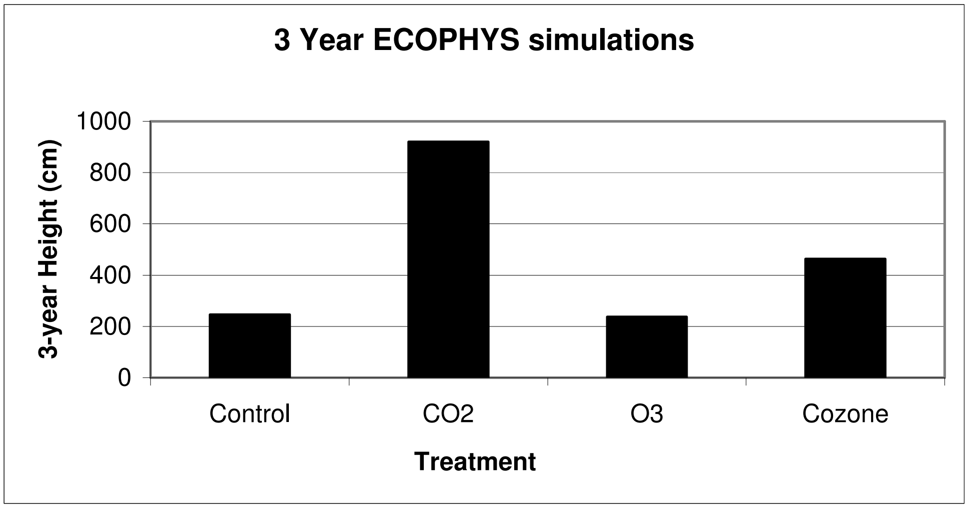
In addition to affecting internode length, leaf initiation rate also affects the number of leaves on a tree. The 1999 data from the Aspen FACE site showed that there were significantly fewer leaves on a tree at the bud-set date than Ecophys predicted with a fixed leaf initiation rate of 37 hrs. (control field conditions).

Simulated total leaf number is also affected by algorithms and parameters in Ecophys besides leaf initiation rate. These include the in-season leaf death algorithm, the acquisition and distribution of carbon within the tree, the modeling of bud set, and branch and bud death algorithms.

3.4 Simulating Aspen FACE Height and Diameter Growth

Setting the leaf initiation rate in Ecophys to 46 hrs, based on calibration to 3rd year control field data, simulations were run with Aspen FACE data from elevated O_3, elevated CO_2, and Cozone rings. As shown in Figure 7, there were significant height and diameter growth responses to elevated CO_2 that were damped with O_3.

Aspen FACE growth results indicate that elevated O_3 moderates the increased growth effect of CO_2, as it does in Figure 7, except not with respect to height. According to Isebrands et al. (2001), neither elevated O_3 nor elevated CO_2 significantly impacted the height of aspen 259. However, diameter growth differences in the field were significant, with CO_2 increasing diameter growth and O_3 reducing diameter growth as compared to the control. As shown in Figure 7, these qualitative effects on diameter growth were replicated by Ecophys.



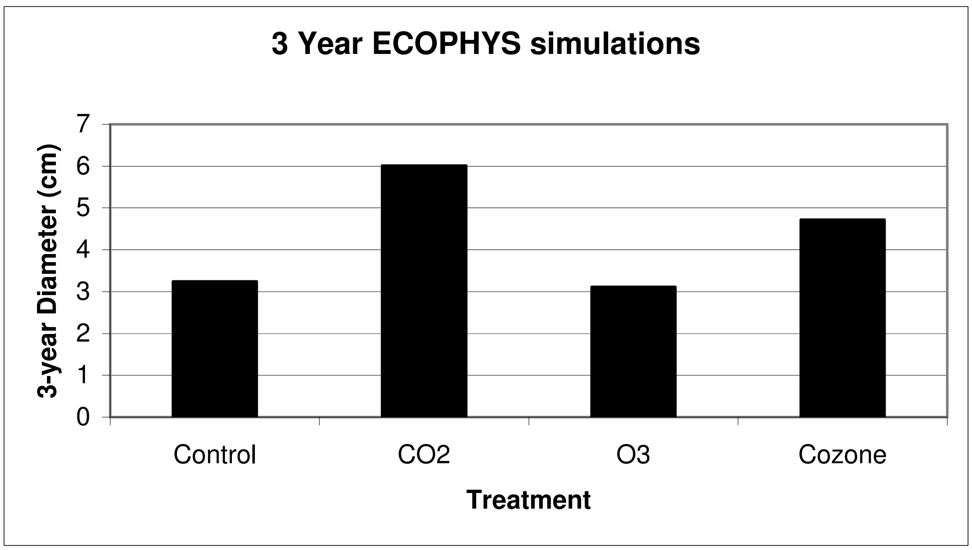


Figure 7

4. Discussion and Future Work

Ecophys relies heavily on leaf-level light interception, the resulting generation of photosynthate, and the transportation of carbohydrate to the various growth centers within the tree. Ecophys modeling and computational advances of these key processes continue to evolve as technological capabilities, new knowledge of physiological processes, and relevant data emerge. See, e.g. Tordsen, (2003), Guan, (2002), Martin et al., (2001), Lenz and Stech, (2000).

There are significant processes affecting tree growth at the Aspen FACE site that are not yet modeled in Ecophys. These include nitrogen and water limitations, loss of tree tissues to insects, viruses, rabbits and ozone, winter die back of shoots and buds, and competition among trees. For example, winter die back observed after the 1999-2000 dormant season was significant. About 34% of the current terminal shoot length for aspen 259 was lost to die back (Isebrands et. al., 2001). Therefore it is expected that, currently, Ecophy's simulated growth will tend to overshoot that observed in the Aspen FACE experiment. Meanwhile, efforts are underway to include the above processes in Ecophys.

Analysis of Aspen FACE morphological and phenological data continues as more data becomes available and further details concerning data collection are considered. Methods discussed in this report will be repeated and extended to include statistical techniques for direct or indirect comparison of model dynamics as well as parameter values with field data.. Sensitivity analysis will be done for various morphological, phenological, and growth parameters and submodels of Ecophys.

Data on leaf drop during the growing season prior to end of season senescence, bud death, and branch abscission will be sought to parameterize Ecophys' growing season leaf drop, bud death, and branch abscission submodels. These submodels are central to determining multiple-year simulated growth of a tree in response to environmental conditions, and beyond that, the simulation of the growth and competition within a patch of trees.

Additional work will be done concerning bud set and senescence rate responses to elevated CO_2 and O_3. Aspen FACE data suggests that elevated CO_2 and elevated O_3 affect the timing of bud set and senescence. Correlation analysis will be done to determine if there is a relationship between elevated CO_2 and delayed bud set and if there is a relationship between elevated O_3 and early bud set.

Several phenological processes such as bud set, senescence, branch death, and leaf initiation rate will be made responsive to photosynthate production and allocation. These and other submodels will be calibrated separately for each simulated aspen clone based on available data.

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Appendix A. Meetings with Aspen FACE Investigators in April and May, 2002.

Meetings were held with various Aspen FACE investigators in order to better understand Aspen FACE data sets and modeling issues. Ecophys group members George Host, Harlan Stech, Kathryn Lenz, Larry Tordsen, Yongtao (Grant) Guan, Kyle Roskoski, and Mariah Olson visited Aspen FACE site in April 2002. While there, we met with Mark Kubiske, Evan McDonald, and Bill Mattson, and Jud Isebrands. We discussed current activities/observations at the Aspen FACE site as well as modeling/simulation Ecophys projects. Undergraduates Kyle Roskoski and Mariah Olson, and master's students Larry Tordsen, and Yongtao Guan gave short presentations of their research efforts (Roskoski, 2002), (Olson, 2002), (Guan, 2002), (Tordsen, 2003) and the Aspen FACE data that we had received to date. Plant physiologists Mark Kubiske and Evan McDonald discussed the physiology of carbon distribution throughout an aspen tree and ideas for modeling carbon distribution in ECOPHYS. Entomologist Bill Mattson discussed various bug and blight infestations that trees at the site have endured. He described damage caused by various bugs and blights and subsequent tree recovery.

Dr. Kubiske, Aspen FACE site coordinator, brought us to the Aspen FACE site. There Kyle Roskoski measured branch diameters and lengths. The trees were dormant and the gas was off.

In May 2002, Jud Isebrands met with us at UMD to further discuss carbon distribution within a tree. He explained in more detail how trees distribute photosynthate and discussed some ideas about how to model this distribution.

2002 Aspen FACE Harvest: The week of July 15th through July 19th, 2002, Mariah Olson and Kyle Roskoski participated in the two-week long biomass harvest at the Aspen FACE site in Rhinelander, WI. They took measurements and weights of branches and leaves from the harvested trees from within the experiment. The harvest involved digging up four trees from each ring to obtain measurements of coarse roots, fine roots, branches and leaves.

Appendix B

Table B.1 lists the Julian days for the 1999 bud-break, bud-set and the leaf senescence start date for each ring and treatment based on Aspen Face data, followed by the resulting Ecophys parameters.

Bud-break	bud-set	senescence start	ring	years
137	230	235	Ring 1.1	1998, 1999
137	196	246	Ring 2.1	1998, 1999
137	238	263	Ring 3.1	1998, 1999
137	246	269	Ring 1.2	1998, 1999
137	230	266	Ring 2.2	1998, 1999
137	246	269	Ring 3.2	1998, 1999
137	225	239	Ring 1.3	1998, 1999
137	196	215	Ring 2.3	1998, 1999
137	230	246	Ring 3.3	1998, 1999
137	215	250	Ring 1.4	1998, 1999
137	215	245	Ring 2.4	1998, 1999
137	215	237	Ring 3.4	1998, 1999
Ecophys parameter values				
137	230	246	Control	
137	246	269	CO_2	
137	225	239	O_3	
137	215	245	CO_2 and O_3	

Table B.1

Table B.2 lists measurements taken by Kyle Roskoski at that Aspen FACE site in April, 2002. These measurements have been compared with results of ECOPHYS test runs.

Ring 1.1	
Aspen 216	
From Ground to first branch	46cm
	30cm
From Ground to second branch	40cm
Ring 1.2	
Aspen 216	
Length of LS	180-190cm
Ring 1.3	
Aspen 259	
From Ground to first branch	16cm
	11-20cm
Length of LS	90cm
	64cm
	54cm
Ring 1.4	
Aspen 259	
Length of SS	2.5-5cm
Internode Lengths	2-3cm
Length of LS	46cm
	20cm
	18cm
	10cm