Mod97-2



**FINAL**

# Nutrient and Fire Disturbance and Model Evaluation Documentation for the Across Trophic Level System Simulation (ATLSS)

Report Prepared for the
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# 1.0 INTRODUCTION

## 1.1 Document Objectives

The information presented in this document organizes and synthesizes data from the scientific literature to enable the inclusion of nutrient enrichment and fire as agents of plant community succession into the Across Trophic Level Systems Simulation (ATLSS). The ATLSS covers the Florida peninsula from Lake Okechobee southward and uses plant communities defined by the Florida GAP (FGAP) analysis (version 6.6) as its basic ecosystem units. The plant community disturbances caused by nutrient enrichment and fire are designed to be integrated with hydrologic and fire disturbances and the community succession tables found in Wetzel (2001).

This document is divided into five sections. The first and second sections provide a brief overview of the phosphorus cycle and a general explanation of plant community succession from nutrient enrichment. Then the conditions needed to cause nutrient enrichment succession are outlined. All model assumptions and limitations are noted at each step. The effect of nitrogen enrichment on Everglades' herbaceous plant communities is similarly considered in the third section.

The fourth section outlines the parameters needed to model fire disturbance in the Everglades plant communities. Fire periodicities in other plant communities are detailed in Wetzel (2001). Finally, the fifth section discusses how the plant community succession steps of the ATLSS model can be evaluated to improve the realism of the model and enhance user confidence.

The specific objectives of this document include:

1. Determine the effects of phosphorus and nitrogen surface water enrichment on as many FGAP v. 6.6 plant communities as possible.
2. Develop or obtain from the literature a series of decision rules that guide plant community succession when disturbed with nutrient enrichment. Succession decision rules must include the direction and rate of succession for nutrient disturbance.
3. Determine fire disturbance parameters for Everglades's plant communities including fire periodicity, fire intensity, and annual area burned. Develop or obtain from the literature a series of decision rules that guide plant community succession when disturbed by fire.
4. Describe the limitations and assumptions used in all decision rules.
5. Carefully document all parameter estimation and decision rule algorithms with references from the scientific literature and expert professional opinion.
6. Develop a general outline for a model evaluation procedure of the plant community succession aspects of the ATLSS model.

## 1.2 The Phosphorus Cycle

Phosphorus (P) is a mineral and originates from rock sources in the earth's crust. Unlike carbon and nitrogen, phosphorus has no biologically induced fluxes (such as photosynthesis for carbon and denitrification for nitrogen). Nor does P serve as the primary energy source for microorganisms (Paul & Clark 1989, p. 224). However,

organisms are tightly linked to the cycling of phosphorus in the water and soil. Microorganisms help solubilize inorganic P from sediments and mineralize organic P through decomposition. Plants and especially microorganisms, immobilize available P in the soil and the water column. P limits biological productivity in wetland ecosystems, including the Everglades (Noe et al. 2001).

Phosphorus has many forms and is often separated in the laboratory into forms that have little biological meaning. The total phosphorus cycling through ecosystems occurs in particulate and dissolved forms (Table 1). Particulate P includes P in organisms (nucleic acids, nucleotide phosphates, and enzymes), P in the mineral phases of rock, and P adsorbed onto dead organic matter (Wetzel 2001, p. 240). Dissolved P consists of orthophosphate and a number of organic and inorganic phosphorus compounds (Wetzel 2001, p. 240).

Table 1. Forms of phosphorus categorized by ecosystem "compartment" and by organic and inorganic form.

| Ecosystem Compartment | Form: Organic | Form: Inorganic |
|---|---|---|
| Particulate | P in organisms<br>P adsorbed onto dead organic matter | Mineral phases of rock & soil with P adsorbed onto clays, carbonates |
| Dissolved | Organic colloids, polyphosphates (from detergents), and phosphate esters | Orthophosphate ($PO_4^{3-}$) (Soluble Reactive Phosphate, SRP) |

Historically, the Everglades were P limited or oligotrophic for several reasons. The primary source of P into the Everglades was from atmospheric deposition, contributing 90% of the total. Davis (1994) estimated total P to be 29 $\mu g\ L^{-1}$ in rainfall (wet and dry deposition). Much of the atmospheric P was probably intercepted by floating periphyton mats. Periphyton may use both dissolved inorganic and organic phosphorus and are estimated to sequester ~10% of total P in Everglades soils (Noe et al. 2001).

Little exposed bedrock and no sediment input in the Everglades prevents the weathering of mineral rock and the release of P into the system. Also, groundwater inputs into the Everglades have high pH and calcium (Ca) concentrations. The high pH keeps P compounds insoluble in the water column. The high Ca concentrations enable the periphytic algae to precipitate calcium carbonate ($CaCO_3$) which leads to the precipitation of Ca-P compounds or the co-precipitation of $PO_4$ with $CaCO_3$ (Noe et al. 2001, p. 609). Currently, about 69% of the phosphorus inputs into the Water Conservation Areas and 12% of the phosphorus inputs into the Everglades National Park are anthropogenic in origin and enter through overland flow or are pumped into their respective areas (Davis 1994, p. 362).

Phosphorus is stored in the soil, periphyton and microbial communities, and dead and living plant material. Dissolved phosphorus in the water column is retained by soils and taken up by vegetation and microbes (Richardson and Marshall 1986; Wetzel 1999). A major proportion (30-70%) of the surface soil P in the Everglades is stored in the organic pool, the rest being inorganic P (Reddy et al. 1998). Soils enriched with high nutrient surface waters have a greater proportion of inorganic P (Koch & Reddy, 1992; Reddy et al. 1998).

Microbial and algal storage of P is small, but rapidly cycled through the system. This rapid cycling time may provide the entire system with a steady supply of biologically active P (Reddy et al. 1998). Because such a large proportion of P is stored in living and dead plant material, soil oxidation either by microbial decomposition (especially high when water levels are lowered) or fire can increase available P. On the other hand, soil oxidation and fire may decrease the residual or more recalcitrant forms of P in the soil (Reddy et al. 1998). Thus, P storage in the soil is a function of P loading, accumulation in the soils, and hydrology, as it relates to oxidation and fire disturbance.

### 1.3 Nutrient Disturbance and Plant Community Succession

*Cladium jamaicense* dominated, and continues to dominate, much of the undisturbed Everglades' herbaceous plant communities. It grows in hydroperiods ranging from 130–330 days (Schomer and Drew 1982; Ross et al. 2000). Although *Cladium* may often be phosphorus (P) limited (Daost and Childers 1999), it can survive in low P environments because it can fix carbon at low P levels and efficiently retains P within the plant (Richardson et al. 1999). These capabilities make *Cladium* well adapted to the oligotrophic conditions of the Everglades (Steward and Ornes 1975). It is also well adapted to tolerate drought and fire (Forthman 1973; Urban et al. 1993)

In native plant communities with undisturbed hydroperiods and nutrient levels *Typha domingensis* was a minor component of the Everglades herbaceous communities compared to *Cladium* (Loveless, 1959; Wood and Tanner 1990). *Typha* is found in a hydroperiod range from 180–300 days (Kushan 1990; Schomer and Drew 1982). It also has several physiologic traits that suggest that it has higher nutrient requirements than *Cladium*: higher growth rates, higher P concentrations in leaf tissue, and greater nutrient uptake (Toth 1987, 1988; Davis 1991; Koch and Reddy 1992). *Typha* also tolerates extended (3 years) deepwater hydroperiods (1.15 m) (Grace 1989).

Nutrient enrichment of soil and surface water stimulates *Typha* growth and biomass (Urban et al. 1993; Newman et al. 1996). It stimulates *Cladium* growth too, but not at the same level of magnitude (Newman et al. 1996). The interaction of nutrient enrichment and extended hydroperiod leads to *Typha*'s competitive superiority over *Cladium* and eventual dominance of the plant community (Newman et al. 1996). The pumping of nutrient enriched agricultural runoff into the northern Everglades has tripled the background soil P levels and increased hydroperiods, causing a shift from *Cladium* dominated communities to *Typha* dominated communities in WCA-2A and northern WCA-3A and -3B (DeBusk et al. 1994; Richardson et al. 1999; Vaithiyanathan and Richardson 1999).

However, if soil nutrient levels are high enough to stimulate *Typha* growth but hydroperiods are short, muck fires (very hot fires that burn up to 50 cm of peat) may be

the most important factor that allows *Typha* to dominate the plant community. This is what happened in the generally dry Rotenberger Wildlife Management Area (Newman et al. 1998). It is hypothesized that the dry hydrology allowed muck fires to reduce the peat elevation and create deep water areas that were quickly colonized by *Typha*.

If the soil is moderately enriched with P compared to WCA-2A and hydroperiods are long (9 months) with high water levels (40-60 cm), then hydrology is the most important factor in promoting *Typha* dominance (Newman et al. 1998).

Thus, succession of herbaceous plant communities in the Everglades results from the interaction of three environmental parameters: hydroperiod, nutrient levels, and fire frequency and intensity. Studies that have considered the interaction of these three parameters have focused on three major plant communities: dense cattail, mixed sawgrass and cattail, and sawgrass and sloughs. These communities represent only a small number of FGAP v. 6.6 communities (Table 2), but cover 20.1% of the study area. Equivalent ATLSS plant communities are given in Table 2.

Table 2. FGAP v. 6.6 plant communities that are equivalent to the plant communities for which soil total phosphorus has been measured.

| Nutrient Plant Community Classification | Equivalent FGAP v. 6.6 Plant Communities† |
|---|---|
| Dense Cattail | Cattail Marsh CG [46] |
| Mixed Sawgrass and Cattail | Graminoid Emergent Marsh CG [42]<br>Sawgrass Marsh [43] |
| Sawgrass and Sloughs | Graminoid Emergent Marsh CG [42]<br>Sawgrass Marsh [43]<br>Spikerush Marsh [44]<br>Forb Emergent Marsh [56] |

† Value in brackets is the FGAP v. 6.6 class number.

Unfortunately, nutrient enrichment of other FGAP communities has not been studied. However, a number of the FGAP communities can be assumed to succeed to cattail marsh with nutrient enrichment because a favorable hydrology and fire regime is present. All of the FGAP communities that could reasonably succeed to a cattail dominated plant community include: Dwarf Cypress Prairie [53], Temperate Wet Prairie [54], Graminoid Emergent Marsh [42], Sawgrass Marsh [43], Spikerush Marsh [44], Maidencane Marsh [55], Saturated-Flooded Cold Deciduous Shrubland Ecological Complex (smaller tree islands and the tails of larger tree islands) [37], and Forb Emergent Marsh [56].

## 1.4 General Decision Rules for Nutrient Induced Succession

A short "key" provides an overview of how nutrient enrichment may be incorporated into the ATLSS model. Each step in the key is referenced with the document section numbers where a full explanation is provided. If nutrient enrichment stops, it is assumed that peat accretion continues at historic rates. Once enough peat has covered the nutrient enriched peat layer, it is assumed that total soil phosphorus levels will decline and plant communities will succeed to a species composition similar to historic plant communities. This process is expected to occur in 100–200 years.

1. Model cell within 10 km of a water control structure or levee [*see section 2.1*]..... **2**
1. Model cell not within 10 km of a water control structure; peat accretion continues at historic rate..... **No nutrient enrichment**

2. Model cell north of Alligator Alley (Interstate 75)..... **3**
2. Model cell south of Alligator Alley (Interstate 75); peat accretion continues at historic rate [*see section 2.7*]..... **No nutrient enrichment**

3. Estimate total phosphorus in soil based on distance from water control structure [*section 2.2*]. Estimate total phosphorus accumulation (based on distance from water control structure) in soil that will be added to the initial soil concentration during each model time step [*section 2.3*]..... **4**

4. Soil total phosphorus (at 0-10 cm depth) is below 600 mg $kg^{-1}$–nutrient enriched succession does not occur in current time step [*section 2.4*]..... **1**
4. Soil total phosphorus above 600 mg $kg^{-1}$. Estimate the probability that the plant community in a model cell or part of a cell will succeed to another plant community [*sections 2.4, 2.5*]. Determine possible plant communities based on soil total phosphorus, hydroperiod, and fire regime. If nutrient enriched succession occurs, change plant communities at a given rate [*section 2.6*]. Advance to next time step... **1**

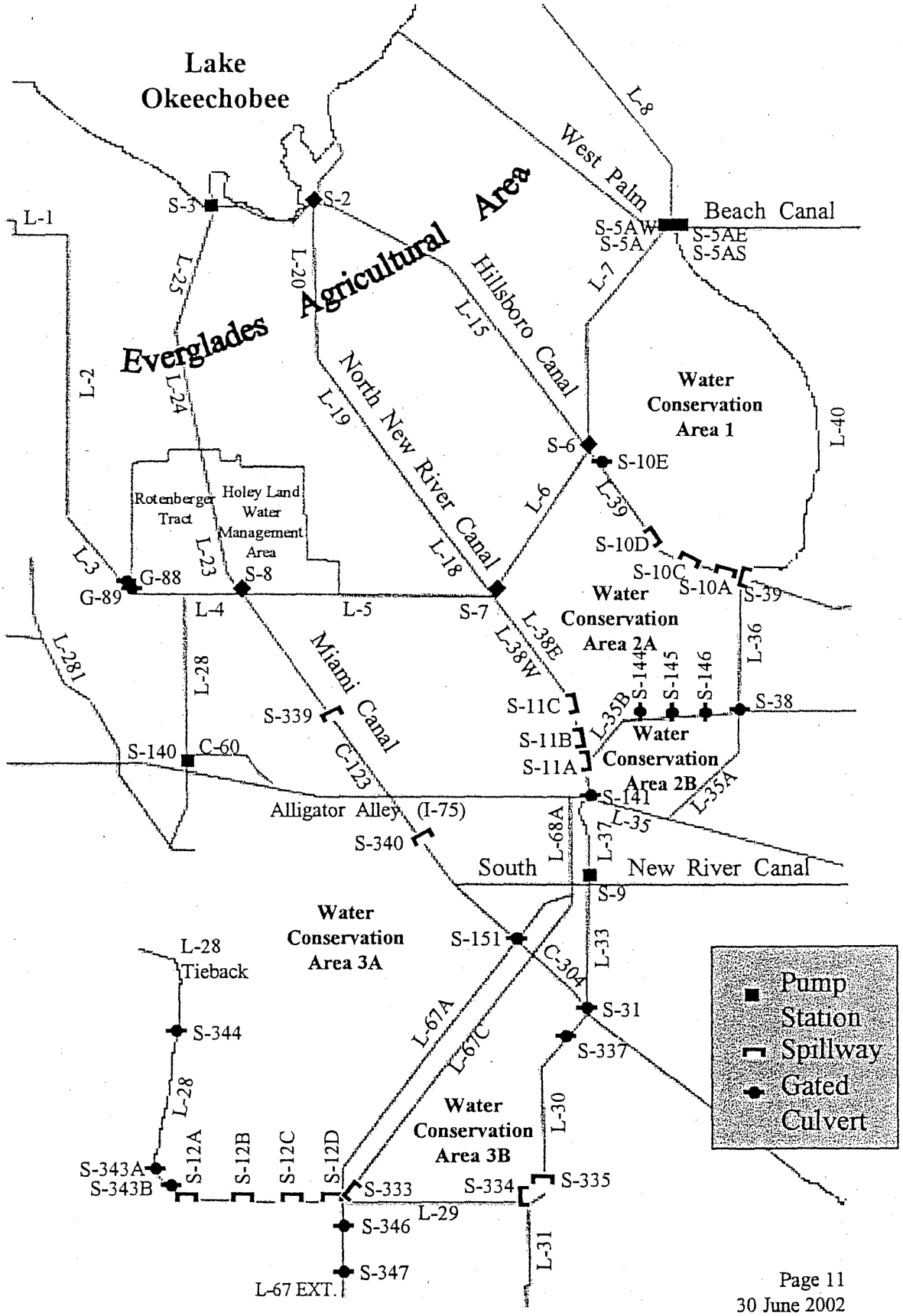
# 2.0 PHOSPHORUS ENRICHMENT MODULE

## 2.1 Water Control Structures

About 69% of the phosphorus inputs into the Water Conservation Areas and 12% of the phosphorus inputs into the Everglades National Park enter through overland flow or are pumped into their respective areas (Davis 1994, p. 362). Water carrying nutrients will "enter" the model landscape from the many water control structures, canals, and levee borrow canals (Figure 1). Water quality statistics and trends are often complicated by hydrologic variations. However, many studies have found that nutrient enrichment in the Everglades is greater in the vicinity of water control structures and canals that discharge runoff from the Everglades Agricultural Area (EAA) (Urban et al. 1993; Koch & Reddy 1993; Reddy et al. 1998; Richardson et al. 1999). The mean total phosphorus levels in surface water measured over the period of record are illustrated on Figure 2 to spatially represent the total phosphorus concentrations throughout the Everglades. Surface water nutrient levels are greater near canals and inflow structures in the northern part of the Everglades, closest to the EAA (Figure 2) (Germain 1998, p. 145-158; SFWMD 1999, p. 4-10). Much of that phosphorus is removed from the surface waters by the time the water reaches the northern boundary of the Everglades National Park, where the mean total phosphorus concentration in the surface waters is at background levels ($<21\ \mu g\ L^{-1}$).

Water Conservation Area 1 and WCA 2A receive the greatest nutrient inputs of the entire system. Precipitation is the largest component of WCA 1's surface water budget (54%) (Newman et al. 1997, p. 1275). Additional surface waters are pumped into the area through S-5A (30%) at the northern tip and through pump station S-6 (15%) on the western side of the Conservation area (Figure 2). Although WCA 1 has a north south slope of 2.6 cm $km^{-1}$, water from the pump stations tends to flow southward through the interior perimeter canal, with most of the water flowing through the L-7 canal into the L-39 canal and finally through structures S-10D, S-10C, and S-10A (Figure 1). Soil contour maps of total P indicate that total P is elevated above background levels around S-5A and S-6 and along the western perimeter canal as far south as the S-10D structure (Newman et al. 1997, Fig. 5, p. 1279).

Figure 1. Map of major canals and water control structures in the Everglades Agricultural Area and Water Conservation Areas (Modified from Light and Dineen 1994, Figure 4.14, p. 73)


Lake Okeechobee
Everglades Agricultural Area
West Palm Beach Canal
Hillsboro Canal
North New River Canal
Miami Canal
South New River Canal
Alligator Alley (I-75)
Rotenberger Tract
Holey Land Water Management Area
Water Conservation Area 1
Water Conservation Area 2A
Water Conservation Area 2B
Water Conservation Area 3A
Water Conservation Area 3B
L-28 Tieback
L-67 EXT.
S-3
S-2
S-5AW
S-5A
S-5AE
S-5AS
S-6
S-10E
S-10D
S-10C
S-10A
S-39
G-88
G-89
S-8
S-7
S-144
S-145
S-146
S-38
S-11C
S-11B
S-11A
S-339
S-140
C-60
S-141
S-340
S-9
S-151
S-31
S-337
S-344
S-343A
S-343B
S-12A
S-12B
S-12C
S-12D
S-333
S-334
S-335
S-346
S-347
L-1
L-2
L-3
L-4
L-5
L-6
L-7
L-8
L-15
L-18
L-19
L-20
L-23
L-24
L-25
L-28
L-29
L-30
L-31
L-33
L-35
L-35A
L-35B
L-36
L-37
L-38E
L-38W
L-39
L-40
L-67A
L-67C
L-68A
L-281
C-123
C-304
Pump Station
Spillway
Gated Culvert

The nutrient enrichment of the WCA 2A is the most widely studied conservation area in the Everglades. Major water discharges into WCA 2A occur through structures S-10D, S-10C, and S-10A (Figure 1). This water comes from the Hillsboro canal and is highly nutrient enriched. The highest P loads come into WCA 2A through S-10D, with downstream decreases at S-10C and then S-10A (Figure 2) (Fitz and Sklar 1999). Water entering through these structures generally flows southward through the wetland and soil total P contour maps clearly indicate a highly enriched area downstream (DeBusk et al. 1994, Fig. 8, p. 549). Water discharged through S-10E has very high P concentrations (>100 $\mu g\ L^{-1}$), but the overall nutrient load is small compared to S-10D because S-10E has $1/10^{th}$ of the water volume capacity. Water also enters WCA 2A from S-7, where water flows eastward into the marshes and then begins to flow southward. Major discharges from WCA 2A occur from the North New River Canal and through the three S-11 structures into WCA 3A (Figure 2). Minor water volumes are discharged south through the S-144-146 structures into WCA 2B and east through S-38 into the C-14 canal (Germain 1998).

In WCA 3A, approximately 25% of the P inputs enter the Area through S-8, located in the northwest corner of the conservation area (Figure 2) (Reddy et al. 1998, p. 1135). All other structures contribute 32% of the P inputs. Precipitation contributes the remaining 43% of the P entering WCA 3A (Reddy et al. 1998, p. 1135).

After flowing southward through WCA 3A and 3B, surface water enters the Everglades National Park (ENP) via water control structures S-12A-D and 17 culverts (not shown on Figure 1) along L-29 between S-333 and S-334 (Figure 1) and flows into the Shark River Slough watershed (Walker 1991). Water also enters through S-332 and flows into the Taylor Slough watershed and through S-18C into the Coastal Basin watershed. Mean total phosphorus in the surface water flowing through S-332 and S-18C is 7 $\mu g\ L^{-1}$ (Walker 1991, Table 1, p. 61). This nutrient level is considered well within the natural range of Everglades' surface waters and nutrient enrichment succession is not expected to occur south of the ENP's northern boundary. Therefore the ENP water control structures were not depicted in Figures 1 and 2.

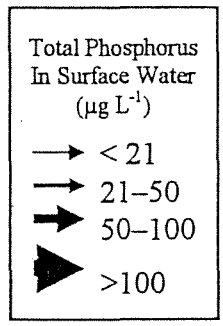
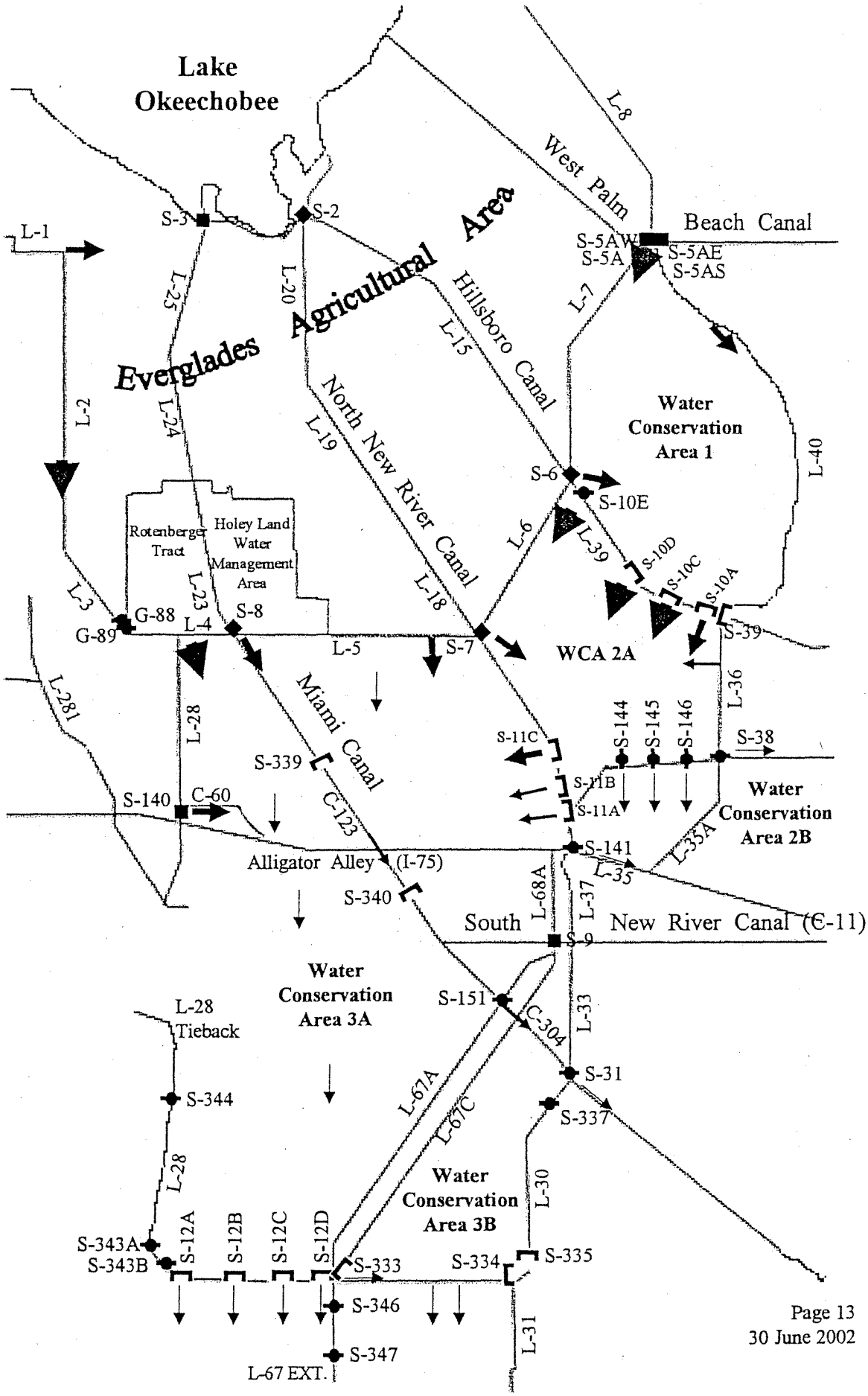



Figure 2. Map of major canals and water control structures in the Everglades Agricultural Area and Water Conservation Areas. Mean total phosphorus concentrations in surface water over period of record are indicated at points along canals, water control structures, and at some interior points with varying sized arrows. Arrow categories correspond to the expected herbaceous plant communities that will occur at that nutrient level (see Table 4). Data from Germain (1998, p. 131-140; p. 145-158).


Lake Okeechobee
Everglades Agricultural Area
West Palm Beach Canal
Hillsboro Canal
North New River Canal
Miami Canal
South New River Canal (C-11)
Alligator Alley (I-75)
Rotenberger Tract
Holey Land Water Management Area
Water Conservation Area 1
Water Conservation Area 2A
Water Conservation Area 2B
Water Conservation Area 3A
Water Conservation Area 3B
L-1
L-2
L-3
L-4
L-5
L-6
L-7
L-8
L-15
L-18
L-19
L-20
L-23
L-24
L-25
L-28
L-281
L-28 Tieback
L-30
L-31
L-33
L-35
L-35A
L-36
L-37
L-39
L-40
L-67A
L-67C
L-68A
L-67 EXT.
C-60
C-123
C-304
S-2
S-3
S-5A
S-5AW
S-5AE
S-5AS
S-6
S-7
S-8
S-9
S-10A
S-10C
S-10D
S-10E
S-11A
S-11B
S-11C
S-12A
S-12B
S-12C
S-12D
S-31
S-38
S-39
S-140
S-141
S-144
S-145
S-146
S-151
S-333
S-334
S-335
S-337
S-339
S-340
S-343A
S-343B
S-344
S-346
S-347
G-88
G-89

## 2.2 Total Phosphorus in Soil (mg $kg^{-1}$)

This model segment provides an initial soil total phosphorus level for the model cells. Baseline or natural phosphorus levels in the Everglades range from 5 to 20 mg $kg^{-1}$. Phosphorus levels are generally higher near water control structures and soil P concentration decreases with distance from the input point, following a first order decay model. These levels are described in the following relationship (Reddy et al. 1998, p. 1143):

$$P_X = P_B + P_{in}\, e^{(-X)} \qquad [1]$$

where $P_X$ is the concentration of total P ($\mu g\ cm^{-3}$) in the top 10 cm depth of soil at distance X (km) from inflow structures or canals; $P_B$ is the background total P in the soil; and $P_{in}$ is the theoretical increase in total P concentration (above background level) at X = 0. Values for the constants $P_B$ and $P_{in}$ are given in Table 3. If needed, constants to calculate total inorganic P and total organic P in the soil as a function of distance can be found in Reddy et al. (1998, Table 4, p. 1143).

Table 3. Mean soil bulk densities (0-10 cm depth) (Reddy et al. 1998, Table 1, p. 1137) and empirical constants for calculating total soil P enrichment (Reddy et al. 1998, Table 4, p. 1143) of selected hydrologic units in the Everglades. $P_B$ is the background total P in the soil and $P_{in}$ is the theoretical increase in total P concentration (above background level). Values in parenthesis in the bulk density column are standard deviations; values in parentheses in the $P_B$ and $P_{in}$ columns are standard errors.

| Location | Bulk Density (g Soil $cm^{-3}$) | $P_B$ ($\mu g\ P\ cm^{-3}$) | $P_{in}$ ($\mu g\ P\ cm^{-3}$) |
|---|---|---|---|
| WCA–1 | 0.06 (0.003) (n=90) | 15.4 (1.6) | 157 (5) |
| WCA–2 | 0.06 (0.02) (n=96) | 45.1 (3.2) | 132 (12) |
| WCA–3 | 0.14 (0.01) (n=188) | 39.5 (5.2) | 206 (20) |
| Holey Land Wildlife Management Area | 0.13 (0.01) (n=36) | 36.9 (13.5) | 277 (31) |
| Rotenberger Wildlife Management Areas* | 0.22 (0.02) (n=31) | – | – |
| Everglades Agricultural Area | 0.42 (0.1) (n=7) | – | – |

* Newman et al. 1998, Table 1, p. 272.

*Model Assumptions*

- Atmospheric and animal P inputs are assumed to be constant and evenly distributed over the model landscape. This assumption is justified because, 1. natural P inputs do not cause landscape level changes in the Everglade's plant communities, and 2. P input from agricultural runoff into the Water Conservation Areas is estimated to be 69% of the total P input (Davis 1994, p. 362), a much larger share than natural inputs.
- Total P accumulated from agricultural drainage inputs (determined using Eq. 2, next section) will be added to $P_B$ each year of the model run. **Therefore, the P enrichment zone will constantly increase in size over time.** The rate of increase in the P enrichment zone may vary, but it will always be positive.
- **Because $P_{in}$ is the theoretical increase in TP concentration above background level, maintaining minimum P levels across the enrichment gradient, the P enriched zone will never shrink from its present day size using Eq. 1.**

*Data Limitations*

- The empirical constants used in Eq. 1 were obtained from 8 sample locations in the Everglades Agricultural Area, one transect in WCA-1, two transects in WCA-2A, and two transects in northern WCA-3A (Reddy et al. 1998, Fig. 1, p. 1135). Therefore, Eq. 1 reflects the specific conditions of those locations during the sample period. Applying the relationship to other locations introduces a certain amount of error into the model.

## 2.3 Total Phosphorus Accumulation (g $m^{-2}$ $year^{-1}$)

Phosphorus accumulation downstream from inflows and near canals is a function of mean annual surface water P concentration (Craft and Richardson 1993a). Both surface water P and P accumulation in peat decrease with distance from the input point, following a first order decay model. This accumulation is added to the total phosphorus concentration of the soil each year. Total phosphorus accumulation (TPA) g $m^{-2}$ $year^{-1}$ is calculated with the following equation (Reddy et al. 1993, Fig. 7, p. 1153):

$$TPA = 0.758-0.243[\ln X] \qquad [2]$$

where X is distance from an inflow point or canal (km). Eq. 2 is not defined for 0 km and it will be necessary to use a number slightly above zero kilometers to estimate TPA near the input point.

It should be noted that Craft & Richardson (1993a, p. 153) determined that P can be sequestered in Everglades peat at an average rate of 0.44 g/$m^2$/yr.

TPA must be converted to a soil concentration (mg $kg^{-1}$). This is done by assuming a volume depth of 0.10 m and then dividing TPA by 0.10 m to get a total phosphorus by volume (g $m^{-3}$ $year^{-1}$). This value must then be divided by the bulk density of the soil (g $cm^{-3}$). The result is total phosphorus concentration added to the soil (mg $kg^{-1}$) on an annual basis. Soil bulk densities vary in the Everglades and should be taken from Table 3 for a particular location.

*Model Assumptions*

- Phosphorus loads into an area are sequestered through the deposition of P enriched detritus and calcium bound P that precipitates to the sediments (Otsuki and Wetzel 1972; Craft and Richardson 1993a; Reddy et al. 1993). The purpose of this segment is to estimate the amount of P that will be annually loaded into an area and add it to the soil P that already exists. Since the plant communities begin to change when the soil P level reaches a certain level, this segment controls P build up in an area and therefore the expansion of certain plant communities. This is the only model segment that enables the model to predict future changes in the expansion or contraction of the P enriched area. **Estimates made by this method represent net accumulation and do not estimate P losses in the system, i.e. P lost during fires or oxidation of peat during drawdowns.**
- The soil depth of 0-10 cm is assumed to be the most active and influential soil layer on the plant communities. Eighty-five percent of the root biomass of aquatic macrophytes extends to the first 15 cm and 100% in the first 30 cm (Richardson and Marshall 1986, p. 288). Vertical gradients of TP generally drop off sharply at about 10 cm depth (Craft and Richardson 1993a, Fig. 3, p. 143; Reddy et al. 1993, Fig. 3, p. 1151). However, lower soil P levels do increase with P enrichment as deep as 45 cm, especially near inflow points (Craft and Richardson 1993a, Fig. 3, p. 143; Reddy et al. 1998, Fig. 2, p. 1138, Fig. 7, p. 1141).

*Data Limitations*

- Equation 2 was developed from samples along one transect in WCA-2A located due south of water control structure S-10C. Thus, the relationship reflects the specific conditions of that one location during the sample period. Applying the relationship to other locations introduces a certain amount of error into the model.
- Craft and Richardson (1993a) also report total phosphorus accumulation as a function of distance from inflow points. In their study, three transects were sampled directly south of water control structures S-10D, S-10C, and S-10A respectively. Total phosphorus accumulation (TPA) g $m^{-2}$ $year^{-1}$ is calculated with the following equation (Fig. 5, p. 151):

$$TPA = 0.90 - 0.152(X) + 0.007(X)^2 \; ; \; r^2 = 0.98 \qquad [3]$$

where X is distance from inflow or canal (km). Samples used to create Eq. 3 were collected between 1.4 and 10.8 km from the inflow point. Therefore, the range of X in Eq. 3 must be between 1.4 and 10.8 km. Although this equation is the average of three transects, it was not used because the transects started 1.4-1.8 km from the inflow point. Reddy et al. (1993) began sampling at the inflow point and the inclusion of this additional sample changed the TPA equation. However, where the two figures overlap on the x-axis they are very similar.

## 2.4 Relating Plant Communities to Phosphorus Levels in Soil and Water

Whether the plant community in a cell will change from sawgrass to cattail has been considered two ways in the literature. One method of changing plant communities in a cell is to create thresholds of soil TP. Once the soil TP reaches the threshold value, then the plant community changes. This technique is used in the Everglades Landscape Model (ELM) (C. Fitz, South Florida Water Management District, personal communication). Soil TP ranges for different plant communities are given in Table 4. TP values <600 mg $kg^{-1}$ will result in sawgrass and slough communities, values between 600 and 1000 mg $kg^{-1}$ are mixed sawgrass and cattail, and cattail dominates when the soil TP is > 1000 mg $kg^{-1}$ (Table 4).

The second method for determining whether the plant community in the model cell will succeed from sawgrass to cattail uses the spatial location and soil TP to calculate the probability that succession will occur (Wu et al. 1997, p. 271-273). Wu et al. (1997) combined a series of Markov transition probabilities to predict when sawgrass changes to cattail ($Prob_{sawcat}$):

$$Prob_{sawcat} = \varepsilon\ (Prob_{ad} + Prob_{ct} + Prob_{cl} + Prob_{Pe}) \qquad [4]$$

The components of Equation 4 are explained below.

- Effective Coefficient ($\varepsilon$)

$$\varepsilon = (Prob_{TP} \times Prob_{TP}) \times 4.0 \qquad [5]$$

- Soil Total Phosphorus (TP)

$$Prob_{TP} = 1/(1 + 60.781e^{-0.0066TP}) \qquad [6]$$

  This equation describes the correlation between the probability of cattail occurrence in the landscape and TP soil concentration ($r^2 = 0.83$, significant at $p<0.001$). The highest rate of cattail invasion occurred at soil TP of 650 mg $kg^{-1}$ and began to slow as TP increased beyond 650 mg $kg^{-1}$.

- Cattail in Adjacent Cells ($Prob_{ad}$)

$$Prob_{ad} = [0.049\ \ 0.052\ \ 0.061\ \ 0.065\ \ 0.069\ \ 0.072\ \ 0.076\ \ 0.094] \qquad [7]$$

This spatial transition matrix for a Markov chain simulation comes from an analysis of the plant communities in WCA-2A on aerial photographs from 1971, 1976, 1982, 1987, and 1991 (n = 4) divided into 20 × 20 m cells. The mean annual probability of a sawgrass cell changing into a cattail cell based on the number of adjacent cattail cells was estimated through the study period. The results indicated that the number of cattail cells adjacent to a sawgrass cell influences the spatial dynamics of whether the plant community changes or not.

Table 4. Phosphorus and nitrogen ranges in soil and water and the plant communities that grow in those ranges. Recommended P nutrient ranges for ATLSS are also given.

| Nutrient Constituent and Information Source | Plant Community | | | |
|---|---|---|---|---|
| | Dense Cattail | Mixed Sawgrass and Cattail | Sawgrass and Sloughs | Slough/Wet Prairie |
| **Total P in Soil (mg kg$^{-1}$)** | | | | |
| DeBusk et al. 1994, Table 2, p. 546. Values from WCA-2A, 0-10 cm depth, averaged over space, Mean ± one standard deviation and range given. | 1338 ± 381<br>1719 – 957<br>(n = 12) | 802 ± 444<br>1246 – 358<br>(n = 13) | 473 ± 134<br>607 – 339<br>(n = 49) | – |
| Richardson et al. 1999, Fig. 2, p. 2185. Values from WCA-2A along one transect, 0-10 cm depth, averaged over 6 years | > 1050 | 1050 – 630 | <630 | – |
| Jensen et al. 1999, Table 1, p. 679. Values from WCA-2A, 0-5 cm depth, averaged over space, mean ± standard deviation and range given. Ranges from data in Table 1. | 1485 ± 118<br>1781 – 1355<br>(n = 12) | 933 ± 209<br>1290 – 677<br>(n = 12) | 461 ± 76<br>531 – 315<br>(n = 10) | – |
| Noe et al. 2001, Table 2, p. 610. Mean ± 95% confidence interval. Data from literature review that covers the entire Everglades and includes the above studies; number in parentheses is number of studies used to calculate mean. Ranges are mean ± 95% confidence interval. | 1402.9 ± 165.6 (15)<br>1569 – 1237 | 947.3 ± 230.5 (10)<br>1177 – 717 | 533.2 ± 94.0 (20)<br>627 – 439 | 467.1 ± 116.1 (10)<br>583 – 351 |
| **Recommended ATLSS range** | **1800 – 1000** | **1000 – 600** | **<600** | **<600** |
| **Total P in Water (µg L$^{-1}$)** | | | | |
| Richardson et al. 1999, Fig. 2, p. 2185. Values from WCA-2A, 0-10 cm depth, averaged over 6 years | > 50 | 50 – 21 | < 21 | – |
| Noe et al. 2001, Table 2, p. 610. Mean ± 95% confidence interval. Data from literature review that covers the entire Everglades and includes the above studies; number in parentheses is number of studies used to calculate mean. Ranges are mean ± 95% confidence interval. | 76.1 ± 38.8 (5)<br>115 – 37 | 42.3 ± 36.2 (5)<br>78 – 6 | 10.8 ± 4.8 (5)<br>16 – 6 | 10.4 ± 2.5 (8)<br>13 – 7 |
| **Organic P in Soil (mg kg$^{-1}$)** | | | | |
| DeBusk et al. 1994, Table 2, p. 546. Values from WCA-2A, 0-10 cm depth, averaged over space, ± standard deviation | 909 ± 340<br>(n = 12) | 500 ± 202<br>(n = 13) | 322 ± 92<br>(n = 49) | – |
| **Inorganic P in Soil (mg kg$^{-1}$)** | | | | |
| DeBusk et al. 1994, Table 2, p. 546. Values from WCA-2A, 0-10 cm depth, averaged over space, ± standard deviation | 429 ± 116<br>(n = 12) | 302 ± 292<br>(n = 13) | 152 ± 77<br>(n = 49) | – |

Table 4 continued. Phosphorus and nitrogen ranges in soil and water and the plant communities that grow in those ranges.

| Nutrient Constituent and Information Source | Plant Community | | | |
|---|---|---|---|---|
| | Dense Cattail | Mixed Sawgrass and Cattail | Sawgrass and Sloughs | Slough/Wet Prairie |
| **Soluble Reactive P in Soil Porewater (mg $L^{-1}$)** | | | | |
| DeBusk et al. 1994, Table 2, p. 546. Values from WCA-2A, 0-10 cm depth, averaged over space, ± standard deviation | 611 ± 34 (n = 12) | 449 ± 42 (n = 13) | 107 ± 19 (n = 49) | – |
| **Total Nitrogen in Soil (g $kg^{-1}$)** | | | | |
| DeBusk et al. 1994, Table 2, p. 546. Values from WCA-2A, 0-10 cm depth, averaged over space, ± standard deviation | 23.8 ± 5.0 (n = 12) | 28.1 ± 4.9 (n = 13) | 28.7 ± 4.7 (n = 49) | – |

Biologically, this appears to be an estimate of propagule dispersal and environmental conditions.

- Proportion of Cattail Cells in the Landscape ($Prob_{ct}$)

$$Prob_{ct} = f(p) = 0.003 + 0.114p \qquad [8]$$

If a sawgrass cell had no adjacent cattail cells then the probability function was calculated as a proportion of the total cattail cells in the landscape ($p$) ($r^2 = 0.873$, $p<0.05$).

- Proximity of Cell to Canal or Levee ($Prob_{cl}$)

$$Prob_{cl} = 0.049 \qquad [9]$$

Analysis of the probability of sawgrass cells changing to cattail near canals or levees was measured over the study period. The mean probability was 0.049.

- Relationship of Cattail to Water Depth ($Prob_{Pe}$)

$$Prob_{Pe} = (Prob_{TP} + 0.227WD/TP) \times 0.0556 \qquad [10]$$

where WD = water depth (cm) ($r^2 = 0.87$, $p<0.001$).
Spatial analysis over the study period correlated cattail invasion with an increase in water depth, but only where the soil TP concentration were low.

The model developed by Wu et al. (1997) includes many important spatially dependent variables in determining if an area will change from a sawgrass dominated community to a cattail dominated community such as soil TP, water depth, proximity to

anthropogenic sources of P, and propagule dispersal (proximity of sawgrass cell to cattail cells). The simulated vegetation landscape of the Wu et al. (1997) model matched the actual 1991 vegetation landscape with an accuracy of 73%.

However, their model appears to be slightly weighted towards cattail invasion in several ways. For example, if a sawgrass cell had no adjacent cattail cells then a transition probability was calculated as a function of the proportion of the total cattail cells in the landscape (Eq. 8). This is a reasonable function for sawgrass cells near the cattail front, but it becomes less reasonable for sawgrass cells in the isolated, non-enriched areas of the Everglades.

The second way that the overall transition probability is weighted toward cattail conversion is the inclusion of $Prob_{cl}$ in Eq. 9. Because P is introduced into the Everglades through canals and water control structures, soil TP is inherently a function of distance from these structures. Increasing the probability of a transition because of the proximity of a cell to a canal or water control structure double counts the P in a particular area. It may be advisable to leave the transition probabilities $Prob_{ct}$ and $Prob_{cl}$ out of ATLSS unless they are needed.

It should also be noted that $\varepsilon$, $Prob_{ct}$, and $Prob_{Pe}$ will decrease if soil TP levels decrease. $Prob_{ad}$ and $Prob_{cl}$ are constants and will not decrease if soil TP levels decrease. This means that a certain amount the transition probability will be weighted toward the conversion of sawgrass to cattails.

*Data Limitations*

- Data from DeBusk et al. (1994), and Jensen et al. (1999) to a certain extent, were collected widely across WCA-2A increasing the confidence of the data. However, all of the data that correlates nutrient levels with plant communities was collected only from WCA-2A and reflects the specific conditions of that area. Applying the relationship to other locations introduces a certain amount of error into the model.
- The plant communities are broadly defined. Richardson et al. (1999, Fig. 3, p. 2186) is the only reference to give plant cover values of the three P enrichment categories. Although there is a gradient of plant communities through the P enrichment zone it is not exact. For example, *Cladium* can cover over 50% of the plots in the highly enriched zone. However, *Typha* never occupies more than 5% cover of any plots in the non-enriched zone.

## 2.5 Specific Plant Community Changes

Once the total phosphorus (TP) levels have reached a certain threshold, the plant communities will begin to succeed from sawgrass dominated to cattail dominated communities. The specific FGAP v. 6.6 plant community succession in various nutrient and fire conditions is the subject of this section.

Table 5 depicts changes in plant communities at above background and background TP soil levels and various fire disturbances. In Table 5, the hydrologic regime is assumed to remain constant. Successional changes from hydrology should be taken from Tables 4 and 5 in Wetzel (2001). Generally, nutrient level is the driving factor

Table 5. FGAP v. 6.6 plant community succession with nutrient enrichment and surface or muck fire disturbance. Hydrologic regime is assumed to remain constant.

| Initial Plant Community | Nutrient Level | Specific Disturbance | Plant Community After Succession |
|---|---|---|---|
| Muhly Grass Marsh [45] **60–120**<br>Sparsely Wooded Wet Prairie CG [52] **60–120**<br>Dwarf Cypress Prairie [53] **120–150** | Above Background (Soil TP >600 mg $kg^{-1}$) | Surface Fire | Muhly Grass Marsh [45] **60–120**<br>Sparsely Wooded Wet Prairie CG [52] **60–120**<br>Dwarf Cypress Prairie [53] **120–150** |
| Graminoid Marsh CG [42] **120–270**<br>*Cladium* [43] **130–330**<br>*Eleocharis* [44] **150–300** | Above Background (Soil TP >600 mg $kg^{-1}$) | Surface Fire | Graminoid Marsh CG [42] **120–270**<br>*Cladium* [43] **130–330**<br>*Eleocharis* [44] **150–300**<br>*Typha* [46] **180–280** |
| Forb Emergent Marsh [56] **230–360** | Above Background (Soil TP >600 mg $kg^{-1}$) | Surface Fire | *Typha* [46] **180–280** |
| Decid. Shrub [37] **110–320**<br>Swamp Forest CG [17] **120–290** | Above Background (Soil TP >600 mg $kg^{-1}$) | Surface Fire | *Typha* [46] **180–280** |
| Muhly Grass Marsh [45] **60–120**<br>Sparsely Wooded Wet Prairie CG [52] **60–120**<br>Dwarf Cypress Prairie [53] **120–150** | Above Background (Soil TP >600 mg $kg^{-1}$) | Muck Fire | *Typha* [46] **180–280** |
| Graminoid Marsh CG [42] **120–270**<br>*Cladium* [43] **130–330**<br>*Eleocharis* [44] **150–300** | Above Background (Soil TP >600 mg $kg^{-1}$) | Muck Fire | *Typha* [46] **180–280** |
| Forb Emergent Marsh [56] **230–360** | Above Background (Soil TP >600 mg $kg^{-1}$) | Muck Fire | *Typha* [46] **180–280**<br>Floating Leaved Veg. [57] **330–360** |
| Decid. Shrub [37] **110–320**<br>Swamp Forest CG [17] **120–290** | Above Background (Soil TP >600 mg $kg^{-1}$) | Muck Fire | *Typha* [46] **180–280**<br>Graminoid Marsh CG [42] **120–270**<br>*Cladium* [43] **130–330** |
| Muhly Grass Marsh [45] **60–120**<br>Sparsely Wooded Wet Prairie CG [52] **60–120**<br>Dwarf Cypress Prairie [53] **120–150** | Background (Soil TP <600 mg $kg^{-1}$) | Muck Fire | Graminoid Marsh CG [42] **120–270**<br>*Cladium* [43] **130–330**<br>*Eleocharis* [44] **150–300** |
| Graminoid Marsh CG [42] **120–270**<br>*Cladium* [43] **130–330**<br>*Eleocharis* [44] **150–300** | Background (Soil TP <600 mg $kg^{-1}$) | Muck Fire | Forb Emergent Marsh [56] **230–360**<br>Floating Leaved Veg. [57] **330–360** |
| Forb Emergent Marsh [56] **230–360** | Background (Soil TP <600 mg $kg^{-1}$) | Muck Fire | Forb Emergent Marsh [56] **230–360**<br>Floating Leaved Veg. [57] **330–360** |
| Decid. Shrub [37] **110–320**<br>Swamp Forest CG [17] **120–290** | Background (Soil TP <600 mg $kg^{-1}$) | Muck Fire | Graminoid Marsh CG [42] **120–270**<br>*Cladium* [43] **130–330**<br>*Eleocharis* [44] **150–300** |
| Decid. Shrub [37] **110–320**<br>Swamp Forest CG [17] **120–290** | Background (Soil TP <600 mg $kg^{-1}$) | Increased Hydroperiod | Graminoid Marsh CG [42] **120–270**<br>*Cladium* [43] **130–330**<br>*Eleocharis* [44] **150–300** |
| Decid. Shrub [37] **110–320**<br>Swamp Forest CG [17] **120–290** | Above Background (Soil TP >600 mg $kg^{-1}$) | Increased Hydroperiod | *Typha* [46] **180–280** |

in plant community succession when the system has only been disturbed by surface fires. **If nutrient levels are at background levels when surface fires occur, the plant communities, both herbaceous and woody, are maintained** (see Wetzel 2001, Table 4). When a muck fire occurs, nutrient level and the assumed decrease in peat elevation both affect the outcome of plant community succession. The rate of succession or the aerial proportions of the various plant communities have not been accounted for in Table 5 of this report.

## 2.6 Rate of Plant Community Change

Thus far, the interaction of total phosphorus (TP) levels, hydroperiod, and fire disturbance has resulted in a certain plant succession pathway for the FGAP plant communities. Once the successional pathway is determined, then the plant communities will begin to succeed from, for example, sawgrass dominated to cattail dominated communities. The rate of this successional change is the subject of Section 2.6. There is little data on how fast disturbed sawgrass communities succeed to cattail communities, but all available data has been either directly or indirectly related to soil TP concentration. All data comes from the study of WCA-2A.

Richardson et al. (1999) monitored the frequency of sawgrass and cattail for six years in a highly enriched zone, a moderately enriched zone, and in a non-enriched zone (Table 6). When enriched, *Typha* frequency changed nearly 12% annually and only about 2% annually in the moderately enriched zone. This represents a rate of change and could be either expansion or contraction of one species or another. Note that in the non-enriched area *Cladium* frequency changed about 6% annually (Table 6), expanding or contracting with other graminoid marsh or slough plant communities. These data are highly variable and indicate that the plant communities are quite dynamic. Clearly, other factors, such as hydroperiod, fire disturbance or proximity to similar plant communities, affect the rate of plant community change.

Table 6. Mean and range of annual rate of plant community change (% frequency) over a 6 year period along a nutrient gradient in WCA-2A (Richardson et al. 1999, Fig. 3, p. 2186).

| Nutrient Status | Plant Community | Mean (± std. dev.) Annual Expansion or Contraction (%) | | Annual Range of Expansion or Contraction (%) |
|---|---|---|---|---|
| Enriched | Cattail | *Typha* | 11.7 ± 8.8 (n = 2) | 5 – 25 |
| | | *Cladium* | 12.7 ± 7.5 (n = 2) | 2 – 22 |
| Moderately Enriched | Mixed Sawgrass and Cattail | *Typha* | 1.6 ± 1.9 (n = 2) | 0 – 5 |
| | | *Cladium* | 4.1 ± 5.0 (n = 2) | 0 – 13.5 |
| Non-enriched | Sawgrass and Sloughs | *Typha* | – | – |
| | | *Cladium* | 6.3 ± 4.8 (n = 2) | 0 – 13.5 |

Using historic aerial photographs of WCA-2A from 1973 to 1991, Wu et al. (1997, p. 268) found that the yearly invasion rate of cattails increased from 1% in 1973 to 4% by 1987. No differentiation of invasion rates between enriched through non-enriched areas was made. Nor was density considered in the model. Once cattails entered a cell, that cell was designated a cattail cell. The 4% annual invasion rate may be considered an overall landscape rate of community change.

Annual density changes of sawgrass and cattail were measured in plots selected across a hydrologic and nutrient gradient in WCA-2A and were related to hydroperiod by Urban et al. (Figure 3) (1993, Fig. 6, p. 213). Although the plots in Figure 3 have hydroperiod on the x-axis, the interactive effect of nutrients is inherent in the quadratic formula because the data was collected from plots located in the nutrient enriched, moderately enriched, and non-enriched plant zones of WCA-2A.

In general, sawgrass densities decreased as hydroperiod increased and cattail densities increased as hydroperiod increased. This follows the results of other experimental and field studies (Newman et al. 1996, 1998), but the densities were highly variable and the quadratic regression equations for sawgrass and cattail have $r^2$ values of 0.35 and 0.39 respectively (Figure 3). The variability in density probably was affected by both drought and wet years and one fire during the study period.

*Data Limitations*

- The rate of change data from Richardson et al. (1999) is highly variable, but probably the easiest to use. It is important to realize that the plant communities in the moderately and non-enriched areas are not monotypic stands of one species, so rates of change do not always go in one direction. Although the regressions are not statistically strong, I think the idea of tying rate plant community change to hydroperiod is biologically superior (i.e. Urban et al. 1993). Annual density changes are not exactly the same as mean rate of change, but relative density changes could be converted to rate of change by assuming maximum sawgrass densities of 2400 (from Steward & Ornes 1975; Urban et al. 1993) and maximum cattail densities of 800 (Urban et al. 1993). This means that negative densities would be subtracted from the maximum density level and once the density went to zero or below a reasonable minimum (such as 100 stems), then the cell would be converted to a new plant community. Positive density changes would be added to the previous year's value until the maximum was reached. Once the maximum or a reasonable proportion (~ 80%) of a particular plant species density was reached the cell would become that particular plant community in the model.

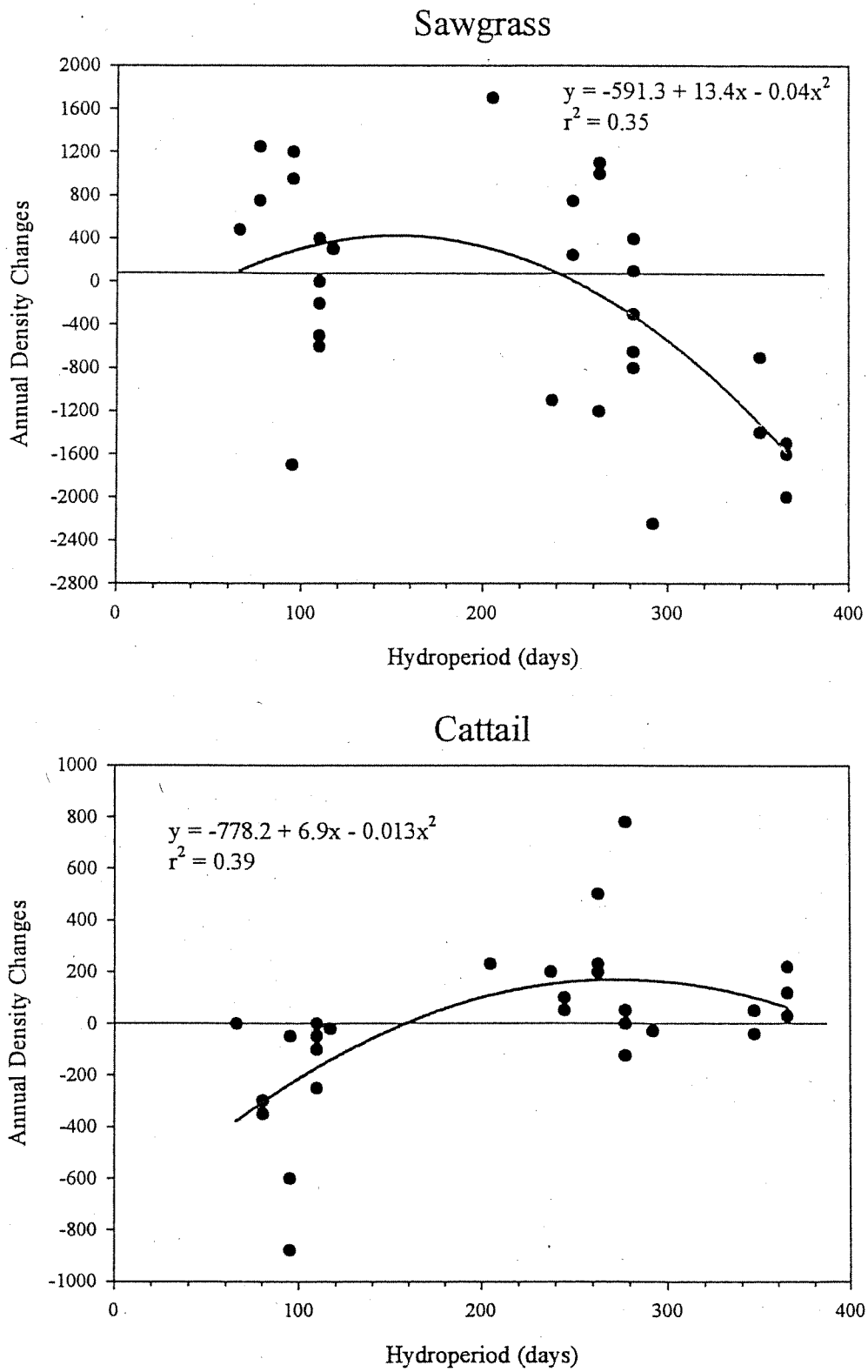



Figure 3. Annual density changes in sawgrass and cattail communities along a nutrient gradient WCA-2A related to hydroperiod. Measurements made from 1986 to 1991. Data from Urban et al. (1993, Fig. 6, p. 213).

## 2.7 Reversing the Cattail Community Expansion

Thus far, the model segments are designed to predict plant community change from nutrient enrichment and the expansion of the cattail community. There is no mechanism to reverse total soil phosphorus levels or the expansion of the cattail community. Such a mechanism is needed to provide ATLSS with long-term predictive capabilities. Craft and Richardson (1993a, p. 148) point out that peatlands are generally poor P sinks and the Everglades are no exception. However, of the P stored in the soil about 85% of the P exists as compounds not easily decomposed or available to organisms (Craft and Richardson 1993a, p. 150). Still, a mechanism is needed to reverse the expansion of the cattail community if high nutrient inputs into surface waters are stopped.

There are two possible ways to contract the P enrichment zone once P inputs are reduced. One option is to burn the peat during a severe (muck) fire that combusts 5-10 cm or more of peat and the P stored in that peat. Reducing soil P through a fire disturbance requires knowing the frequency and size of fire events. It also requires that small changes in elevation be accounted for in the model.

The second way to reduce soil P is to bury the enriched peat through peat formation. As peat accumulates, the enriched peat is compressed and chemically and physically out of reach of the plants and the microbial population. As the soil TP decreases, the vegetation communities will slowly change to a native composition and the P enrichment area will contract.

Mean peat accretion rates in the Everglades have been estimated to range from 1-4 mm $yr^{-1}$ (Gleason et al. 1974, p. 301; Meeder et al. 1996; Reddy et al. 1993, Table 2, p. 1151; SFWMD 1999, p. 2-22). The most realistic scenario would be to randomize the peat accretion rate each annual model run to account for differences in weather conditions. If that is not possible, it is recommended that the ATLSS model use a middle (2 mm $yr^{-1}$) or high value (3 mm $yr^{-1}$) of peat accretion. Once 10 cm of un-enriched peat has accumulated in a model cell (in 50 years at the 2 mm $yr^{-1}$ rate) then the plant communities could begin to change. By the time 20 cm of un-enriched peat had accumulated in an area it should be assumed that the P in the enriched peat is no longer available to the ecosystem and that the plant communities would no longer be disturbed by nutrient enrichment.

# 3.0 NITROGEN ENRICHMENT MODULE

As discussed earlier, the Everglades are phosphorus limited (although several less dominant macrophyte species appear nitrogen limited (Daoust & Childers 1999, p. 262)) and enrichment of surface waters has been observed to cause succession in herbaceous plant communities. However, enriched surface waters entering the Everglades also have high levels of nitrogen. Although nitrogen and phosphorus enrichment occurs together, nitrogen enrichment does not appear to produce plant community succession the way that P enrichment does. While total nitrogen levels were elevated near inflows, no statistically significant accumulation of nitrogen occurred along transects downstream of water inflow structures (Koch & Reddy 1992, p. 1496; Reddy et al. 1993, p. 1153; Urban et al. 1993, p. 210; Vaithiyanathan & Richardson 1999, p. 1349). Nor do nitrogen levels change significantly with soil depth (up to 40 cm deep) (Koch & Reddy 1992, p. 1495; Reddy et al. 1998, p. 1152). When nitrogen was added to the Everglades marsh without additional P, herbaceous plant productivity and nitrogen tissue levels were not significantly different from controls even after two years (Craft & Richardson 1995, p. 267). Thus, the effects of nitrogen enrichment on plant communities have not been studied in the Everglades.

Why does nitrogen enrichment not follow the same patterns as P enrichment? Nitrogen cycling in wetlands is microbially controlled. Nitrogen accumulation does not occur in the Everglades because 1. $NH_4^+$ (the result of the decomposition of organic N) loses a proton at high pH levels, causing the $NH_3$ gas to readily volatilize (Reddy et al. 1993, p. 1153; Wetzel 2001, p. 214), and 2. the highly organic soils sustain high rates of denitrification (Reddy et al. 1993, p. 1153). The high environmental temperatures, neutral to above neutral pH, and high organic levels keep the microbial populations active and prevent nitrogen accumulation. **For these reasons, nitrogen enrichment is not included in the ATLSS model as an agent of plant community change and succession.**

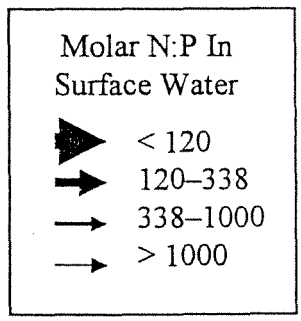
Because surface water inputs contain both nitrogen and phosphorus, it is common to measure the effect of nitrogen enrichment using N:P or molar N:P ratios (Reddy et al. 1993; Noe et al. 2001). Published N:P ratios indicate that the mean soil N:P ratio in enriched areas was 49 and between 145 and 213 in un-enriched areas (Table 7). Figure 4 provides a visual overview of molar N:P ratios around water control structures north of the Everglades National Park. Meta-analysis of N:P ratios averaged for the major herbaceous plant communities, dense cattail, mixed cattail-sawgrass, sawgrass, and slough/wet prairie indicated a statistically significant difference between the enriched (dense cattail and mixed cattail/sawgrass) and un-enriched (sawgrass and slough) plant communities, but no difference between the dense cattail and mixed cattail/sawgrass communities (Table 7) (Noe et al. 2001, p. 610).

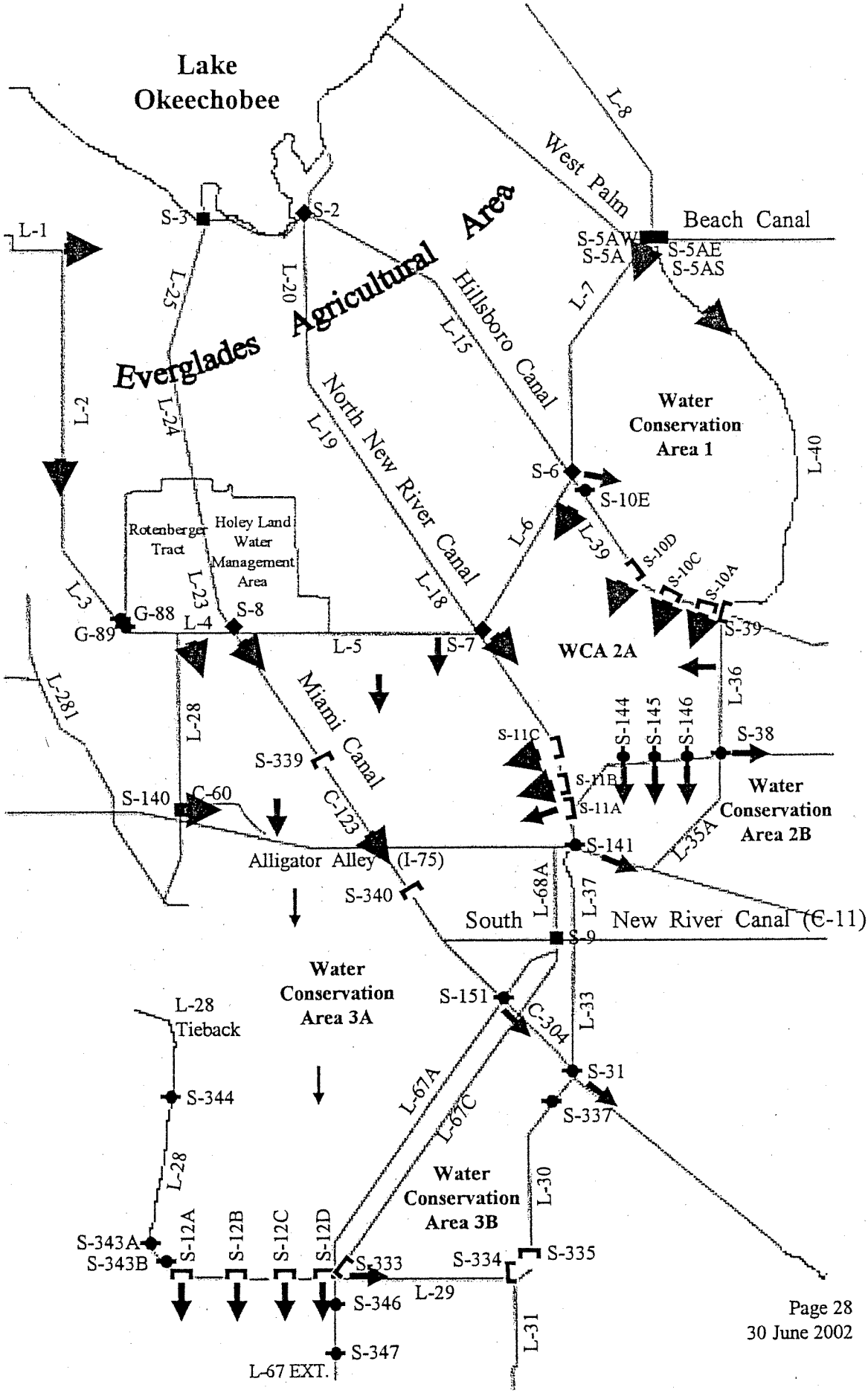
Table 7. Mean molar N:P ratios for various ecosystem components in four major plant communities. Data from Noe et al. (2001), Table 2, p. 610.

| | Plant Community | | | |
|---|---|---|---|---|
| Component | Dense Cattail | Mixed Cattail/Sawgrass | Sawgrass | Slough/Wet Prairie |
| Water N:P | 94.1 ± 52.6 (4)[ab] | 228.0 ± 221.1 (4)[bc] | 542.0 ± 774.8 (3)[c] | 377.6 ± 164.0 (7)[c] |
| Periphyton N:P | – | 86.0 | 165.0 | 151.7 ± 50.2 (4) |
| Soil N:P | 49.0 ± 10.3 (10)[a] | 77.6 ± 20.5 (6)[a] | 144.6 ± 30.2 (12)[b] | 213.0 ± 80.1 (4)[c] |
| Macrophyte N:P | 16.7 ± 9.0 (3)[a] | 40.2 ± 21.8 (4)[b] | 76.7 ± 26.2 (7)[c] | 62.2 ± 53.3 (3)[bc] |

Mean ± 95% confidence interval with sample size (number of studies) in parentheses. Different letters indicate that a statistically significant difference ($\alpha < 0.005$) exists between Everglades plant communities.

Figure 4. Map of major canals and water control structures in the Everglades Agricultural Area and Water Conservation Areas. Molar N:P in surface water over period of record are indicated at points along canals, water control structures, and at some interior points with varying sized arrows. Arrow categories approximately correspond to the expected herbaceous plant communities that will occur at that nutrient level (see Table 7). Data from Germain (1998, p. 131-140; p. 145-158).




Lake Okeechobee
Everglades Agricultural Area
West Palm Beach Canal
L-8
S-3
S-2
L-1
L-25
L-20
L-15
Hillsboro Canal
L-7
S-5AW
S-5A
S-5AE
S-5AS
L-2
L-24
L-19
North New River Canal
Water Conservation Area 1
L-40
S-6
S-10E
L-6
L-39
S-10D
S-10C
S-10A
S-39
Rotenberger Tract
Holey Land Water Management Area
L-23
L-3
G-88
G-89
L-4
S-8
L-5
S-7
L-18
WCA 2A
L-281
L-28
Miami Canal
L-36
S-144
S-145
S-146
S-38
S-11C
S-11B
S-11A
S-339
S-140
C-60
C-123
Water Conservation Area 2B
L-35A
S-141
Alligator Alley (I-75)
S-340
L-68A
L-37
South New River Canal (C-11)
S-9
Water Conservation Area 3A
S-151
C-304
L-33
L-28 Tieback
S-31
S-344
L-67A
L-67C
S-337
L-28
Water Conservation Area 3B
L-30
S-343A
S-343B
S-12A
S-12B
S-12C
S-12D
S-333
S-334
S-335
L-29
S-346
L-31
S-347
L-67 EXT.

# 4.0 FIRE DISTURBANCE

The distinct annual winter dry period and summer wet period weather cycles of the Everglades create conditions that support wildfires. These wildfires, in addition to incendiary (fires started as acts of vandalism) and prescribed fires, create an ecologically important disturbance in many of the plant communities in the project area. This section describes the fire related parameters needed to incorporate fire disturbance into the ATLSS model for the major Everglades' plant communities, the Hammock, Prairie, Marsh, Shrub Island, Bayhead, Slough, and Pond communities. Consistent and complete fire records for the Everglades area of the model are available only from the Everglades National Park and the contiguous areas immediately north of the park boundaries (from 1948 to present). Fire also occurs in other plant communities in the project area and parameters for these plant communities are described in Wetzel (2001).

## 4.1 Determination of Fire Frequency and Annual Burned Area

In the Everglades National Park, the dry season typically begins in early October and extends through April and early May. Precipitation increases in June, with the largest amount of rainfall occurring from June–September (Beckage et al. *in review*). About 70% of the total annual area burned occurs during the transition from the dry to the wet season in April-June. The greatest area (~40% of the total) burned each year burns in May (Gunderson & Snyder 1994, p. 297; Beckage et al. *in review*). However, Taylor (1981, p. 38) reports June as having the greatest acres burned in a month, and April with the second highest area burned per year (Gunderson & Snyder 1994, p. 297; Beckage et al. *in review*). Beckage et al. (*in review*) found that the total area burned in the Everglades National Park was negatively correlated with the dry season water levels (April–May), i.e., when water levels are lowest (correlation coefficient –0.50, $p<0.001$). **It should be noted that water levels used in the analysis were measured at *one* location in the center of Shark River Slough** (Well P33, 25° 36:48.66 N, 80° 42:09.28 W).

The results of a time series analysis of total area burned and dry season water level suggested that fires in the Everglades occur at three different landscape levels (Beckage et al. *in review*, Fig. 2). The total area burned during April through June from 1953-1999 were rank ordered and visually divided into small, medium, and large fire area categories based on natural divisions in the data (Figure 5). The fire area categories were then assigned hectare ranges (Table 8). The time series analysis by Beckage et al. (in review, Table 1) also identified three dominant fire periodicities (Table 8), which are similar to the periodicities reported by Gunderson & Snyder (1994). Data from the Everglades National Park indicates a poor relationship between number of fires and area burned (Gunderson & Snyder 1994, p. 296; Slocum, 2001, Figs. 3, 5, and 6). Generally, 1 or 2 fires burn most of the area burned in a year (B. Beckage, Department of Ecology and Evolutionary Biology, University of Tennessee-Knoxville, personal communication).

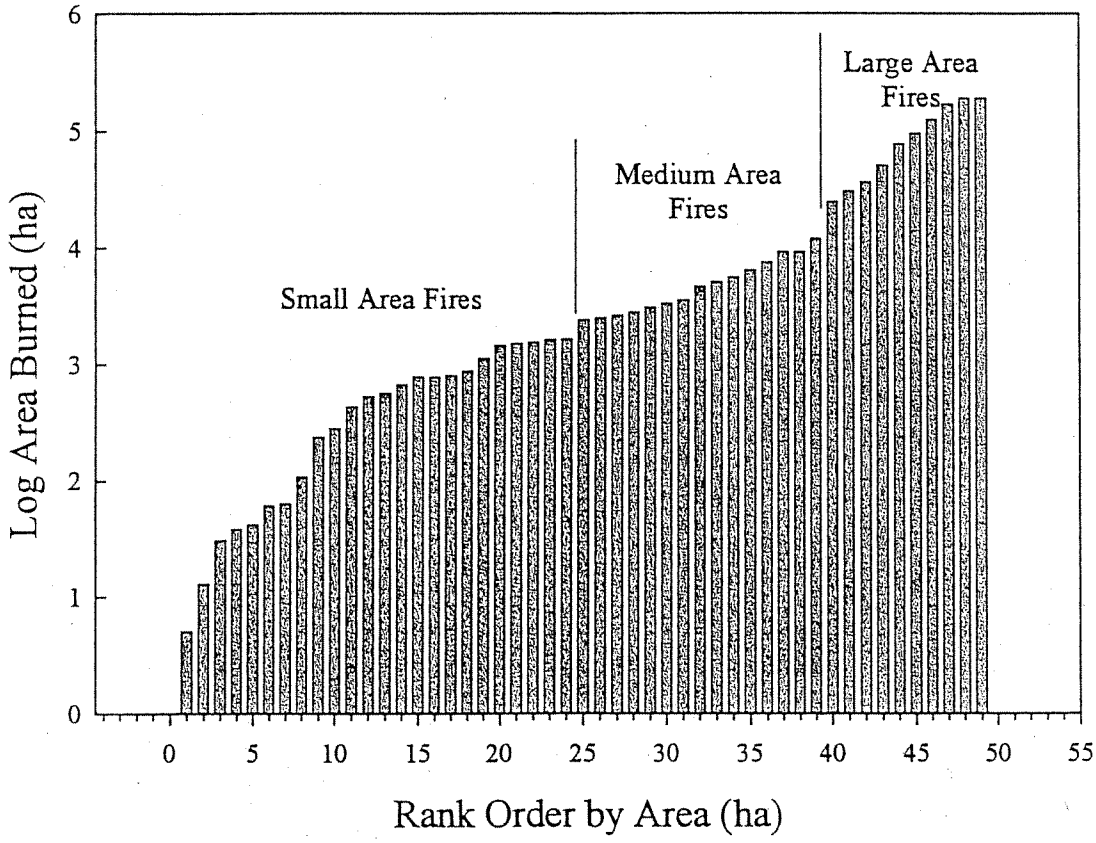



Figure 5. Rank ordering of the log total area burned during April through June in the Everglades National Park, 1953-1999 (Data courtesy of B. Beckage, Department of Ecology and Evolutionary Biology, University of Tennessee-Knoxville). This data was used to visually identify three general landscape level fire areas.

Table 8. Size of areas burned and their frequency of occurrence in a given year in the Everglades National Park (Beckage et al. *in review*, Fig. 2 and Table 1). The estimated area of muck and hammock soil fires, as a percentage of the total area burned in a given year, are indicated for each fire size level (data from Taylor 1981, Figure 4, p. 23). SEM = Standard Error of the Mean.

| Area Burned (ha) | Periodicity (years) | Percent of Burned Area That Muck or Hammock Soil Was Burned (1948-1979) |
|---|---|---|
| 20,000–75,000 | 12.3 | 42 (SEM=11)<br>n = 6 |
| 2,000–20,000 | 5.0 | 33 (SEM= 8)<br>n = 10 |
| 0–2000 | 1.0 | 47 (SEM=11)<br>n = 6 |

The enormous range in area burned over the period of record makes fitting a single line to all of the area data useless. In addition, the area burn data is autocorrelated, i.e., the area burned in the current year depends to some extent on the size of the area burned during the previous years. For example, two large fires could not occur in consecutive years because there would not be enough fuel to sustain large fires one year after another. Thus, the area burned vs. water elevation data was divided into the small, medium, and large area categories identified in Table 8 and a regression line was fitted to each group of data (Figure 6A).

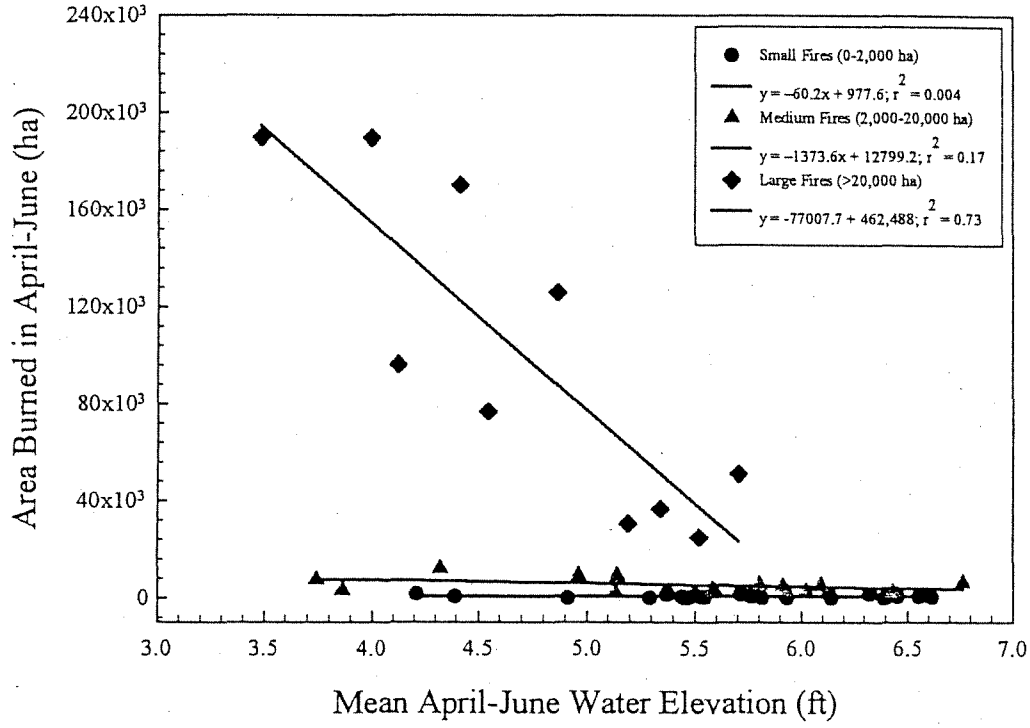
The strongest relationship between mean area burned and mean water level during April-June ($r^2 = 0.73$) was for the large area fires (Figure 6A). Medium area fires had a low correlation ($r^2 = 0.17$) and small fires had no correlation ($r^2 = 0.004$) between mean area burned and mean water level during April-June (Figure 6A). Because of the weak correlation of mean small and medium area burned and water level, these two data sets were plotted together (Figure 6B). However, the correlation of the fitted line to the data was also poor ($r^2 = 0.15$).

Given the available information on fire in the Everglades, the following is suggested as a method to determine the annual area burned in the ATLSS model space. It is assumed that the fire area and periodicity relationships developed by Beckage et al. (*in review*), which were developed from data collected in the Everglades National Park, will be applied to the entire Everglades model area.

Using the average burn periodicity values reported in Table 8, the extent of the burn area (small, medium, and large) is determined. As a minimum up to 2000 ha burns in the Park, and each model year a random number between 0-2000 should be selected as the area burned in the Park. It may be advisable to do this with medium sized fires (2,000–20,000 ha), too. Since the Park is about 35% of the total Everglades model area (all the water conservation areas and the Park, see Davis (1994, Table 15.1, p. 360)), the area burned in the entire Everglades model area (including Conservation Areas) should be adjusted accordingly.

Once the burn area size is determined based on periodicity, then the extent of the burn area is determined using the mean water elevations during April-June regression equation (Figure 6A). The regression equation will work best with large fires and probably poorly with the medium sized burn area category. The fire history of each model cell must be recorded because it is unlikely that the same model cell has enough fuel to burn in consecutive years (see section 4.2 below).

A.




B.

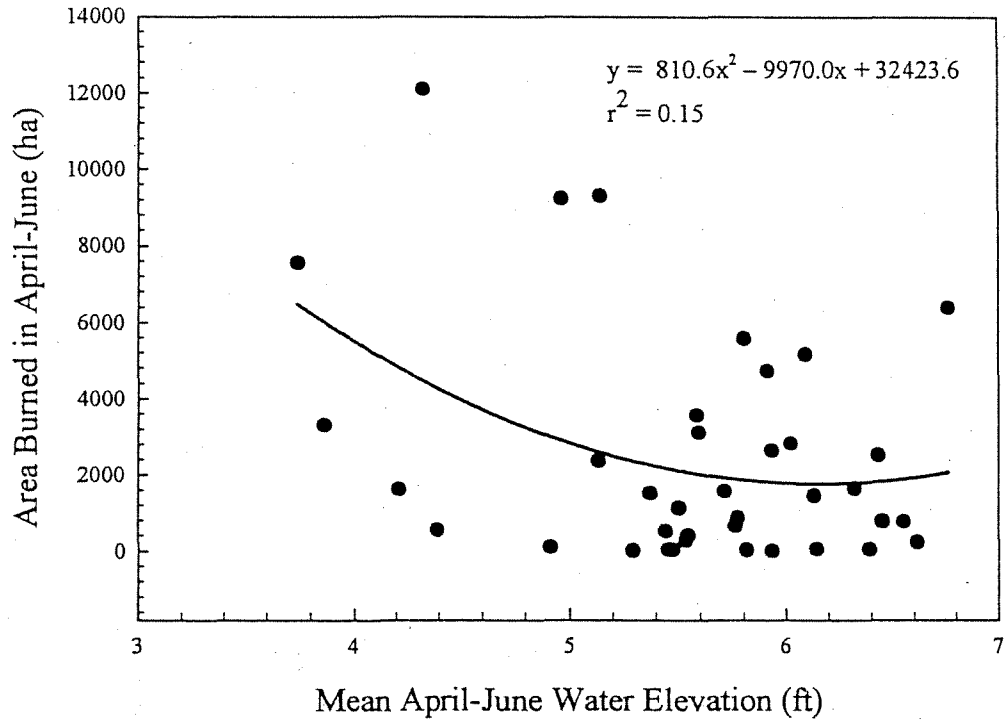



Figure 6. A. Correlation between mean area burned and water elevation during April-June for small, medium, and large fire areas. B. Correlation between mean area burned and water elevation during April-June for small and medium fire areas only.

## 4.2 Fire Intensity

Two general types of fires occur in the Everglades proper: severe peat burning fires or muck fires and less severe or surface fires. Severe peat burning fires may alter plant communities and plant community changes after a fire will depend greatly on the severity of the fire. Severe fires can destroy hammocks and tree islands [Deciduous Shrub, 37] (Loveless 1959, p. 8; Loope and Urban 1980, p. 6, Zaffke 1983, p. 24-25). The oxidation of 10–20 cm of peat after a severe fire may cause wet prairie (Graminoid Marsh CG [42], *Cladium* [43], *Eleocharis* [44], and *Typha* [46]) to succeed into Forb Emergent Marsh [56] or Floating Leaved Vegetation [57] (Loveless 1959, p. 8; Davis et al. 1994, pp. 436–438; Newman et al. 1998, p. 275, 277).

Fires that burn the surface vegetation and not the peat soil generally will not cause one plant community to succeed to another. For example, tropical hardwoods growing on Hammocks are capable of resprouting and rapid recovery after a less severe fire, and survive fires at approximately 5-year intervals (Loope and Urban 1980, p. 6). To a certain extent, less severe fires maintain current plant communities in conjunction with other environmental factors such as hydroperiod, nutrient level, and soil type.

Fire intensity depends on the water level and the fuel load in a plant community because a certain amount of fuel is needed to carry a fire, once it has started. Once an herbaceous plant community has burned, it is estimated that about three years is necessary to restore the plant biomass back to pre-fire levels. Steward and Ornes (1975, p. 166) reported that 18 months after a fire in a sawgrass community, about one third of pre-fire level of biomass had grown back. Schmalzer et al. (1991, p. 67) found that total biomass in *Juncus* (Black Needle Marsh [49]) and *Spartina* (Sand Cordgrass Grassland [48]) marshes was ~30% of the pre-fire levels one year post-fire.

Fire intensity could be incorporated into the ATLSS model in two possible ways. One way would be to determine the water levels and fuel load of each cell. Lower water levels would increase the potential that a muck fire will occur. The "fire" history of each cell must also be known. The longer an individual cell has not burned, the greater the fuel buildup, and the greater the potential for a muck fire to occur. Muck fires would only occur in cells when water levels were very low and fuel load was high (for example has been building up for 8 years or more). If a fire occurred in a model cell within the last two years, than the fuel load would be low and the potential for a surface fire would be low to moderate. The potential for a muck fire in that cell would depend on the water level, but be near zero because of inadequate fuel loads to carry an intense fire.

The second possible method of incorporating fire intensity into the ATLSS model is to assume that a certain amount of the area burned had the intensity of a muck fire. Taylor (1981) reported the amount of area where muck or hammock fires burned in the Everglades National Park from 1948-1979 and this area is highly correlated with total area burned ($r^2 = 0.79$) (Figure 7). During a model fire event, this algorithm will accurately predict the model area designated as having a severe peat fire. The percent area of muck fire (based on the total burned area each year) was also calculated for each fire size and ranged from 33 to 47% (Table 8). Taylor (1981) did not describe how much soil was lost in the area burned by muck fires. Oxidation of 5-10 cm of peat is conservatively suggested, based on anecdotal reports of muck fire burns (Loveless, 1959; Zaffke 1983; Newman et al. 1998).

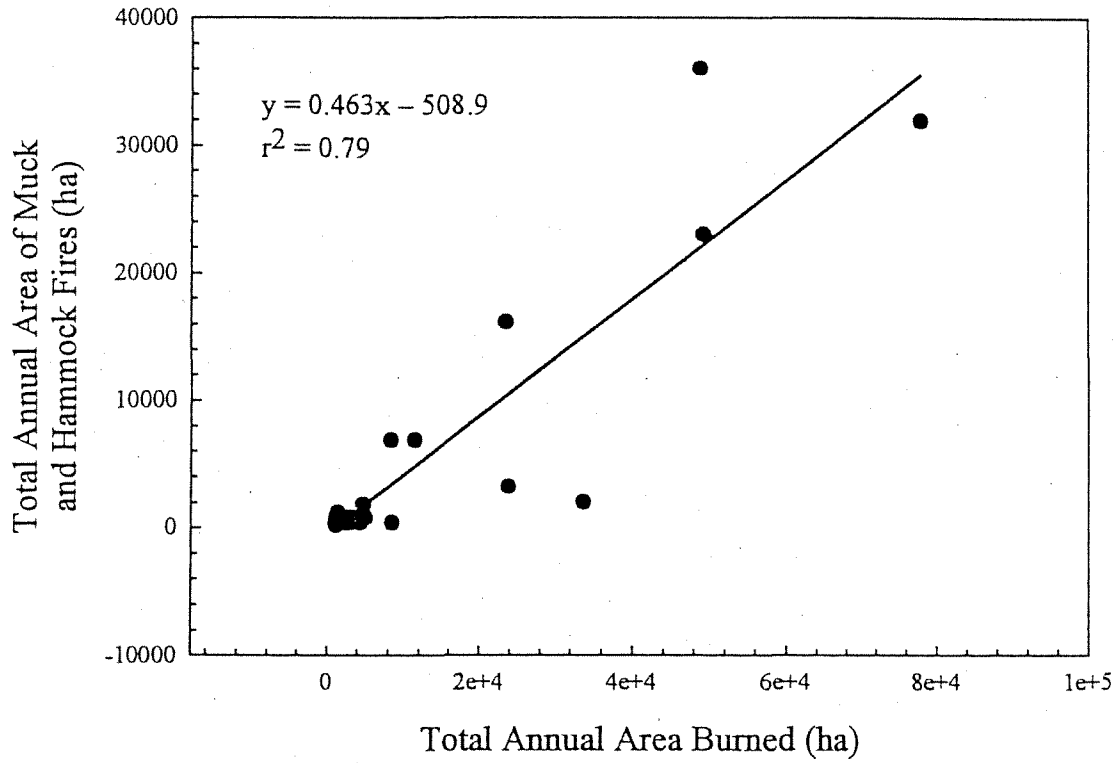



Figure 7. Correlation between annual area burned and area of muck and hammock fires. Data are from Everglades National Park from 1948–1979 (Taylor 1981, p. 23).

### 4.3 Incorporating Fire Disturbance into the ATLSS Model

Fire disturbance can be incorporated into the ATLSS model by developing a fire risk index for each model cell. This fire risk index should be based on the following parameters:

- Dry season (April through June) mean water level or fire periodicity,
- The length of time since the last fire occurred in the cell (to determine fuel load) and the type of fire that last occurred in that cell (fire history), and
- The plant community type. It is expected that herbaceous plant communities will burn more readily than deciduous shrub and floating leaved plant communities.

A decision rule key provides an overview of how fire disturbance can be incorporated into the ATLSS model.

1. Determine size of Everglades area to be burned based on historical fire periodicity and then dry season water level. Check determination; for example large fires (>20,000 ha) should not occur more than every 12-14 years. On average, *up to* 2000 ha of the Everglades burns every year ..... **2**

2. Fire has not occurred in model cell within the last 3 years ..... **3**
2. Fire has occurred in model cell within last 3 years..... **Fire probability low to zero**

3. Fire within last 3 years was a less severe surface fire ..... **4**
3. Fire within last 3 years was a severe muck fire ..... **Fire probability zero**

4. Plant communities are herbaceous and include: Prairie (Dry Prairie EC [29], Muhly Grass Marsh [45], Sparsely Wooded Wet Prairie CG [52], Dwarf Cypress Prairie [53], Temperate Wet Prairie [54]), Marsh (Graminoid Emergent Marsh CG [42], Sawgrass Marsh [43], Spikerush Marsh [44], Cattail Marsh CG [46], Maidencane Marsh [55]), Slough (Forb Emergent Marsh [56]), and Pond (Water Lily or Floating Leaved Vegetation [57]) [*see section 2.5*] ..... **Burn probability moderate to high**
4. Plant communities are woody and include: Hammock (Tropical Hardwood Hammock [2], Buttonwood Woodland [20]), Shrub Island (Broad Leaved Evergreen/Mixed Evergreen Deciduous Shrubland CG [28], Dwarf Mangrove EC [32], Saturated-Flooded Deciduous Shrubland EC [37]), Bayhead (Semi-deciduous Tropical/Subtropical Swamp Forest [3]) [*see section 2.5*] ..... ..... **If current fire disturbance is a surface fire then burn probability low to moderate. If current fire disturbance is severe, then the burn probability is moderate to high**

# 5.0 MODEL EVALUATION

The incorporation of hydrology, fire, and nutrient disturbances to drive plant community succession in the ATLSS model will require an organized and comprehensive model evaluation of the vegetation component. This model evaluation should be designed to answer the simple questions: does the vegetation component of the ATLS Simulation provide a realistic representation of the natural ecosystem that is being modeled? Is the plant community component of ATLSS sufficiently credible to justify its use for resource management decision making?

Bart (1995, p. 412) elaborates a general principle of model evaluation:

> **Models should not be used to make or defend management decisions until they have been thoroughly evaluated and the results of the evaluation have been subjected to peer review. The peer-reviewed model evaluation should be clearly presented and included with the model when it is given to the managers.**

Thus, even if the reliability of a model has not been fully established or it is undergoing successive versions, a substantial effort to evaluate the model is necessary to determine the usefulness and accuracy of its predictions (Bart 1995, p. 412). The general term model evaluation is used in this report because of the disagreement in the literature of how the terms verification and validation are defined and whether a model can even be verified (Oreskes et al. 1994). Definitions of these terms are given in Table 9 for background information.

Table 9. Definitions of model evaluation terms.

| Term | Definition | Source |
|---|---|---|
| Calibration | The estimation and adjustment of model parameters and constants to improve the agreement between model output and a data set. | Rykiel 1996, p. 232 |
| Validation | A demonstration that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model. | Rykiel 1996, p. 233 |
| | Establishment that the model is legitimate or is internally consistent. | Oreskes et al. 1994, p. 642 |
| Verification | A demonstration that the modeling formalism is correct. | Rykiel 1996, p. 232 |
| | An assertion or establishment that the model truly demonstrates ecosystem reality. | Oreskes et al. 1994, p. 641 |

The plant community succession output of the ATLS Simulation is not the primary prediction provided by the model. Rather these outputs are used to drive a series of spatially explicit species index models that enable the comparison of the relative

potential for breeding and/or foraging for several animals across the south Florida landscape (DeAngelis and Gross 2001). Because the plant community succession models are the basis for other linked models, evaluation of just the plant community modules is important and necessary. A comprehensive model evaluation has four components (Bart 1995, p. 412): objectives of the model, description of the model, analysis of model reliability, and synthesis. Each component is discussed below in the context of the ATLSS plant community succession module.

### 5.1 Objectives of the ATLS Simulation

The primary objective of the ATLSS model is to provide a rational, scientific basis for the assessment and ranking of human induced landscape changes in the hydrology and landuse of south Florida. These model assessments provide input to the planning process and an aid to the development of appropriate monitoring and adaptive management schemes for the region. To accomplish this objective, the ATLSS simulates the major physical processes driving the south Florida ecosystem at a landscape level. The outputs of this physical systems model are then used to drive a variety of models that attempt to compare and contrast the relative impacts of alternative human induced hydrologic changes on the system as a whole and on specific individual animal populations (DeAngelis and Gross 2001). It is expected that the ATLSS model will be used in a decision-making and management context. Thus, ATLSS outputs are designed to be interpreted in a relative assessment framework, in which an alternative hydrologic scenario is compared to a base scenario.

### 5.2 Description of the ATLS Simulation

A detailed description of the ATLSS model's general organization, the sequence of steps carried out to generate simulated output, and the underlying assumptions of the model have been widely produced elsewhere (see http://atlss.org for a general overview), although plant community succession and fire and nutrient disturbances have not yet been incorporated into the ATLSS model. Once these sections of the model are written, then their organization, operational processes, and assumptions must be included in the model evaluation.

In brief, the plant community succession pathways are incorporated into the larger ATLS Simulation in the following manner. Course resolution hydrologic information is translated to a high resolution hydrology that is at the appropriate scale of the animal populations that are simulated (see http://www.tiem.utk.edu/~sylv/HTML/Work/Everglades for a general overview of that process). Creation of the high resolution hydrology relies on the FGAP v. 6.6 plant community maps and the associated hydroperiod parameters of each plant community (Wetzel 2001). Spatially explicit species models use the spatially explicit hydrology outputs to compare the relative potential for breeding and/or foraging across the landscape. Thus, any successional change in the plant communities from hydrologic, fire, or nutrient disturbances will change the hydrologic outputs used by the species models.

## 5.3 Analysis of Model Reliability

The model structure and the parameter values used to create the model are an important component of assessing the ATLSS model's reliability. This information, as it pertains to plant communities, is described and documented from the scientific literature in this document and in Wetzel (2001). As part of a peer review model evaluation, the logic of plant community structures and parameter values and model inputs and outputs are evaluated by knowledgeable people. The evaluators are asked if the model is reasonable "on-the-face-of-it" given the model's purpose (Mayer and Butler 1993, p. 22; Rykiel 1996, p. 235).Other methods of assessing the reliability of the ATLSS plant community succession modules are described below.

### 5.3.1 Turing Tests (Rykiel 1996, p. 235)

Simulated data generated by the model are compared visually and statistically to actual data. Knowledgeable people are asked to make an evaluation between the two data sets. Although this technique is widely used (see Fitz et al. 1996), such figures can be deceiving particularly to an untrained reader (Mayer and Butler 1993, p. 23). Mayer and Butler (1993, p. 23-24) recommend plotting the observed (y) vs. predicted ($\hat{y}$) data directly with the line $y = \hat{y}$ to indicate a line of perfect fit to easily see how much the model values deviate from the observed. Fitted regression lines should not be plotted because they may hide any bias from the $y = \hat{y}$ line.

If observed and simulated data can be paired–in time, location, or treatment–then deviance measures between the observed and simulated data are useful (Mayer and Butler 1993, p. 24-25). Mayer and Butler (1993) found that mean absolute error was a more robust measure than mean absolute percent error. Paired data can also be statistically tested using the dimensionless modeling efficiency, EF (Mayer and Butler 1993, p. 27-28). This is similar to the co-efficient of determination, $R^2$, and describes the proportion of the model output variation against the set line $y = \hat{y}$.

Unfortunately, there is little observed data on the landscape level plant community changes in south Florida to compare to simulated output either visually or statistically. In the case of evaluating the plant community responses of the ATLSS model, the only actual landscape plant community data available are historical aerial photographs. Wu et al. (1997) evaluated their model designed to quantify the aerial cover changes in vegetation landscape patterns in Water Conservation Area 2A by comparing actual vegetation maps from 1973 to 1991 with simulated vegetation maps. This could be done with the ATLSS model although such a test would only involve eight plant communities.

Secondary parameters used in the model are good candidates for visual and statistical analysis (Table 10). Observed water levels around the gauges could be compared to predicted water levels, observed burned area compared to predicted burn area, and soil phosphorus levels near human made structures compared to simulated phosphorus levels at the same location. It should be noted comparing predicted observations to historical data is logically circular since the simulation will be based on historical data in the case of hydrology, fire frequency, and soil phosphorus.

Table 10. Possible evaluation variables and standards for the analysis of the ATLS Simulation of plant community succession.

| Evaluation Variable | Expected Changes | Evaluation Standard |
|---|---|---|
| Percent Plant Community Cover | Expect cover of certain plant communities to change in response to changes in hydrology, nutrient load, or fire frequency. | Successional changes compared to short term successional changes reported in the literature. Changes in plant community cover are reasonable and follow expected plant ecology patterns. |
| Fire Frequency | Time series analysis of fire frequency and area burned. | Fire frequency and area burned can be compared to historic data from the Everglades National Park |
| Hydrology | Time series analysis of hydrology (water levels). | Water levels compared to historical data from the South Florida Water Management District. |
| Soil Phosphorus | Simulate phosphorus levels in soil and water column. | Phosphorus levels compared to current known levels on the landscape. |
| Multiple Evaluation Variables | Interaction of multiple variables will result in a variety of scenarios. | Changes in the evaluation variables tested are reasonable and consistent. |

5.3.2 Gradient Response/Extreme–Condition Tests

In this test the model is run under a set of variable conditions that simulate a naturally occurring gradient (Shugart and West 1980, p. 311). Determining whether the model output would change if the parameters, initial values, or equations were different is essentially a sensitivity analysis (Swartzman and Kaluzny 1987, p. 217). These tests cannot be directly compared to actual data, but determine whether the model produces reasonable results over a range of expected conditions. The model is typically deemed sensitive to a particular parameter if changing that parameter's value by 10% leads to more than a 10% change in the output from the baseline simulation (Swartzman and Kaluzny 1987, p. 217; Jackson et al. 2000, p. 704).

Possible evaluation variables are listed in Table 10. The most direct evaluation variable is percent plant community cover. The General Ecosystem Model developed for the Everglades (Fitz et al. 1996, p. 287) was tested by simulating hydrologic, macrophyte, and nutrient variables over time under different levels of phosphorus. However except for WCA 2A, historical community cover data is not readily available. Therefore, evaluating the changes in plant community cover will require peer review from knowledgeable persons.

There are several problems with sensitivity analyses, ranging from interactions between parameters to the cost of model runs (Swartzman and Kaluzny 1987, p. 218). Therefore, the objectives and boundaries of the analysis must be clearly defined

before starting the analysis. A sensitivity analysis consists of a two step process (Swartzman and Kaluzny 1987, p. 220-225): selecting or generating a range of model parameters and making the model runs and then analysis of the model output to determine the parameter sensitivity. Parameters are generated by either systematic sampling or random sampling using Monte Carlo methods.

The simulated plant community succession by the ATLSS model under test gradients of hydrology, fire disturbance, or nutrient disturbance may be difficult to discern over the entire ATLSS project area. Evaluation could be focused in two possible ways: 1. conduct gradient response tests on a well studied general plant community type, such as the Pine/Scrub/Flatwood group, Cypress forest, or the Herbaceous Plant Communities group, or 2. evaluate gradient response tests in a specific, small area. In either case, the simulation of the percent plant community cover should also include the fire frequency, hydrology, and soil phosphorus model simulations that resulted in the plant community cover patterns under evaluation. This will allow a more comprehensive model evaluation.

Extreme or catastrophic environmental gradients could also be simulated by the model (Rykiel 1996, p. 236). An extreme condition test, such as an extended drought (>3 years) or extended wet period (>3 years), would be a better evaluation of the entire ATLSS project area. Presumably such extreme events would have a significant landscape level impact, making changes in the plant communities easier to measure. Again, such tests cannot be directly compared to actual data, but determine whether the model produces reasonable results during extreme environmental conditions.

### 5.3.3 Traces (Rykiel 1996, p. 236)

The behavior of specific variables is traced through the model and simulations to determine if that behavior is reasonable and acceptable. Performing model traces is much easier on clearly defined variables that are invoked frequently through the simulation. Because this part of the ATLSS model lacks clearly defined variables, traces may be of limited usefulness. However, it may be useful to trace a specific plant community or group of related plant communities through a model simulation. Coverage of the plant community could be statistically related to the aerial coverage of that plant community's hydroperiod, fire frequency, and soil nutrient level.

### 5.3.4 Internal Validity (Rykiel 1996, p. 235)

A model's internal validity can be tested by producing a consistent output each time a test data set is run through the model. Again, this does not determine whether the plant community section of the ATLSS model provides a realistic representation of the south Florida ecosystem, but simply indicates whether the model performs consistently.

## 5.4 Synthesis

The synthesis step of a model evaluation involves integrating the results of the evaluation and presenting them in a way that provides a realistic description of the reliability of the model (Bart 1995, p. 414). Bart (1995, p. 414) suggests putting the evaluation results in context of the model output of two sets of parameters: one set that represents the "minimum" environmental scenario and one set that represents the "maximum" environmental scenario. All other scenarios or model runs can than be interpreted between the two extremes by the peer reviewers.

Model evaluation in general, and particularly an evaluation of ATLSS, should also consider whether the model improves the ability of natural resource managers to make decisions (Bart 1995, p. 414). The synthesis step of the evaluation must include a clear discussion of the model limitations and how the model should be used in natural resource management decision making.

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