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A Literature Review

Karen Malone and Hans Williams

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**Abstract:** The definition of growing season in the 1987 U.S. Army Corps of Engineers Wetland Delineation Manual is derived from the soil biological-zero temperature concept. Lacking direct information on soil temperatures, minimum air temperature thresholds are used as indicators of the beginning and ending dates for the growing season. The 1987 Manual regional supplements allow for field observations of above-ground plant growth to estimate the growing season period. Since acceptance of the 1987 Manual, the growing season concept has been controversial. Soil biological zero does not apply to large areas of the continental United States, minimum air temperature thresholds appear inconsistent with observations of above- and below-ground biological activity, and photoperiodism and thermoperiodism result in local, regional, and annual variations for determining the growing season period based on plant activity. Additionally, the belief that wetlands perform ecological functions year round supports the argument that defining the growing season is irrelevant. A literature review of the environmental factors that influence above- and below-ground biological activity is presented. Recommendations are made on the use of the growing season concept to support jurisdictional wetland delineation determinations.

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## **Preface**

The report was prepared by Karen Malone and Hans Williams, both of the Arthur Temple College of Forestry and Agriculture, Division of Environmental Science, Stephen F. Austin State University, under the direction of Robert H. Lichvar, Remote Sensing/Geographic Information Systems and Water Resources Branch (RR-C), U.S. Army Engineer Research and Development Center – Cold Regions Research and Engineering Laboratory (ERDC-CRREL).

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# 1 Introduction

In 1987, after many years of development and testing, the U.S. Army Corps of Engineers (USACE) published the *Wetland Delineation Manual*, also known as the 1987 Manual (Environmental Laboratory 1987). The purpose of the 1987 Manual is “...to provide users with guidelines and methods to determine whether an area is a wetland for purposes of Section 404 of the Clean Water Act (CWA).” As outlined in the 1987 Manual, the three-factor approach to delineating a wetland requires identifying wetland hydrology, hydric soil, and hydrophytic vegetation. According to the 1987 Manual, after the growing season has been determined, it is essential to establish that “...a wetland area is periodically inundated or has saturated soils during the growing season.”

The “growing season” concept in the development and field identification of wetland hydrology and hydric soils has been controversial. Appendix A of the 1987 Manual defines “growing season” as:

“...the portion of the year when soil temperatures at 19.7 inches (50 cm) below the soil surface are higher than biological zero (50°C) (U.S. Department of Agriculture – Soil Conservation Service 1985). For ease of determination this period can be approximated by the number of frost-free days (U.S. Geological Survey 1970).”

The user notes (on page 29 of the online version of the 1987 Manual) further define growing season by adding the following guideline:

“Estimated starting and ending dates for the growing season are based on 28°F (–2.2°C) air temperature thresholds at a frequency of 5 years in 10 (HQUSACE, 6 Mar 92).”

In the 6 March 1992 memorandum of clarification from Headquarters USACE (HQUSACE) (Williams 1992), the USACE allowed districts in the south the discretion to use an air temperature of 32°F instead of 28°F. The 1987 Manual includes the 1985 Soil Conservation Service’s definition of “growing season” within its definition of hydric soil: “...a soil that is saturated, flooded, or ponded long enough during the growing season to



develop anaerobic conditions that favor the growth and regeneration of hydrophytic vegetation” (U.S. Department of Agriculture-Soil Conservation Service 1985). The National Technical Committee for Hydric Soils (NTCHS) defines “long duration” as ranging from seven days to one month during the growing season. The lack of a specified duration for saturated, flooded, or ponded conditions has led to a dilemma for those attempting to standardize terminology across the U.S. In an attempt to address the difficulty, the National Research Council (NRC) (1995) concluded that “the threshold for duration of saturation can be approximated as 14 consecutive days during the growing season in most years (long-term mean exceeding 50% of years). The depth over which saturation should be evaluated is the upper plant rooting zone, which can be estimated as 1 ft (30 cm).” The 14-day duration was not based on scientific data but was an attempt to create a solution until scientific evidence could be collected. The growing season concept remained in the NRC duration recommendation. The NRC acknowledged that there would likely be regional variations due to climate, geography, vegetation, and other factors. Standardization issues arise from the range of wetland classes and temperature zones across the U.S. Higher latitudes, increased altitude, the Hawaiian Islands, and the arctic region (including Alaska) present exceptions and ensuing quandaries.

According to the NRC, the current concept of growing season cannot be applied reliably, and a more credible system for defining saturation thresholds needs to be developed, suggesting that “two general possibilities exist for resolving the problems caused by the use of growing season in the identification of wetlands: 1) Abandon growing season as a constraint on the duration threshold for inundation and saturation and replace it with a system that links duration with temperature, or 2) Redefine the growing season by region on the basis of careful scientific study of natural wetland communities and processes.” Currently, there are ten USACE regional wetland delineation supplements (USACE 2007, 2008a-e, 2009a-b, in prep. a,b) to the 1987 Manual that are approved or in the approval process. These supplements address the recommendation to emphasize regionalization and were developed by regional working groups made up of experts in wetlands ecology and regulation. The supplements use the 14-consecutive-day duration during the growing season in most years for wetland hydrology recommended by the NRC.

Each of the regional supplements bases its growing season definition on the 1987 Manual but allows the growing season of a wetland to be determined by above-ground observations of plant growth and/or a below-ground measure of soil temperature. Above-ground observations established as indicators of growth by the regional working groups provide appreciable evidence demonstrating that by the time soil reaches the required temperature, or the frost-free requirement is met, multiple above-ground growing season indicators will be well established for multiple species. However, for temperate zones, the cessation of above-ground growth in the fall and the beginning of growth in the spring is determined by a complex set of plant responses to thermoperiod and photoperiod. The responses to thermoperiod and photoperiod are species specific, and genetic variability occurs within a species. Dormancy, or the cessation of seasonal growth, is primarily driven by the decreasing length of the day (photoperiod). The winter dormancy cycle includes pre-rest, rest, and post-rest phases (Kimmins 2004). The transition from rest to post-rest is mediated by the plant's response to chilling temperatures. The resumption of growth in the spring is in response to the accumulation of heat sums, often measured in units of degree-days or degree-hours. Seeds from herbaceous and woody plants also have thermoperiod and photoperiod requirements that must be met before they will germinate.

The rationale for below-ground temperature standards is based in agricultural practices. The concept is that soil temperature influences root elongation, which is a form of plant growth that is difficult to observe in the field. The agricultural basis of this concept ignores the below-ground activity of microbes, which is essential for the development of hydric soil and the performance of some wetland functions (Rabenhorst 2005). Below-ground microbial activity is a necessary component of wetland ecology, but microbial activity is not limited to the temperature range dictated by the growing season definition of the 1987 Manual (Shaver and Billings 1997; Rabenhorst 2005). Several studies (Megonigal et al. 1996; Seybold et al. 2002; Burdt et al. 2005) have shown that microbial activity occurs year round in the southern and coastal regions.

The objective of this review is to examine the relationship between the term "growing season" as it is defined in the 1987 Manual and the following ecological activities:

- Above-ground plant response to the thermoperiod/photoperiod cycle;

- Above-ground plant phenological response to flooding/soil saturation;
- Below-ground plant response to soil temperature;
- Below-ground microbial response to soil temperature; and
- Above-ground plant response to microbial activity.

The review concludes with a summary of issues related to the use of the growing season concept and recommendations for solutions and further research.

## **2 Ecological Activities and the Growing Season**

### **2.1 Above-ground plant response to the thermoperiod/photoperiod cycle**

#### **2.1.1 Thermoperiod**

Of all the environmental factors influencing plant behavior, temperature is most easily measured. Accordingly, the literature on temperature and plant response is abundant, dating back as far as 1735 (Wang 1960). Air, plant, and soil temperatures have been measured extensively, and variations in each lead to different vegetation responses. The range of temperatures in which plants can grow and thrive is exceptionally broad. Plants demonstrate extensive physiological and biochemical adaptations to the range of geographical location and environmental temperature. The biological response of a plant to a particular temperature reflects the adaptation of the plant to that temperature. As would be expected, plant species native to cooler climates do not require temperatures as high as plants of warmer climates for growth and other processes. The three most significant geographical variables affecting temperature are latitude, altitude, and proximity to large bodies of water. Aspect and topographic position are also important determinants of local temperature and environmental conditions (Kimmins 2004). Plants also experience diurnal temperature variation, and those that do not live in the equatorial zone experience seasonal temperature fluctuations. The adaptation of plants to their particular diurnal and seasonal temperature changes is a phenomenon known as thermoperiodism.

Most studies of plant response to temperature have focused on agricultural crop production and have been carried out in controlled settings in an attempt to reduce the number of complex variables found in situ. This simplification often makes it difficult to apply the data to native plants in the field. Regardless, whether in controlled or native environments, years of observation and study confirm that "...plant responses to temperature can be expressed in terms of three fundamental temperatures: the minimum and maximum temperatures at which the process ceases entirely, and the optimum range of temperature over which the highest rate can be maintained, assuming temperature is the limiting

factor” (Fitter and Hay 2002). These minimum, maximum, and optimal temperatures are known as cardinal temperatures. Plants and their parts (especially above- and below-ground growth) have different cardinal temperatures for growth, development, and survival. Stem growth responds to ambient air temperature. Root growth responds to soil temperature. Leaf growth is contingent on temperatures that can vary, depending on evapotranspiration, thickness of leaf, and location in the canopy, among other things (Fitter and Hay 2002).

Diurnal temperature differences can determine important processes such as flowering and fruiting (Treshow 1970) and maximum growth height (Kramer 1957; Hellmers and Sundahl 1959). Daytime fluctuations can influence plant growth as well. Criddle et al. (1997) demonstrated that the cold-climate cultivar cabbage (*Brassica oleracea* L. *capitata*) and the warm-climate cultivar tomato (*Lycopersicon esculentum*) have growth rates that differ constantly with daytime temperature fluctuations. Often, temperature fluctuations are more conducive to plant growth and physiological processes than a constant optimal temperature. A slight change in temperature, even briefly, may affect physiological and biochemical processes of plants to a great degree (Singla et al. 1996).

Above-ground plant responses to seasonal temperature fluctuations are most numerous, observable, and measurable in the spring. Many thermal indices have been developed to predict spring planting, flowering, and maturity in agricultural crops based on accumulation of heat sums (Wang 1960). This temperature–time concept is applicable in non-agricultural settings as well. Generally, as temperature rises, the rate of plant processes accelerates to a maximum and then declines beyond a specific optimum temperature for the plant species. Degree-days have allowed the determination of plant cardinal temperatures for many species-specific growth indicators such as bud burst in trees (Thomson and Moncrief 1982; Hunter and Lechowicz 1992), pollen shedding (Boyer 1978), flowering in several range plants (White 1979), anthesis and maturity of wheat (*Triticum aestivum*) and corn (*Zea mays*) (Gilmore and Rodgers 1958; Cross and Zuber 1972; Davidson and Campbell 1983; Bauer et al. 1984), and the germination and emergence of multiple plant species (Carberry and Campbell 1989; Jordan and Haferkamp 1989).

Temperature influences the rate at which resources become available to plants. Resource acquisition is associated with the warm temperatures of

spring and summer, but plant adaptation allows growth to be maintained by native vegetation in arctic and other cold environments. In spite of the harsh conditions and low temperatures, studies have shown that phenological development does occur in the low ambient temperatures of arctic and alpine tundra ecosystems (Holway and Ward 1965; Fitter et al. 1995; Dunne et al. 2003). Chapin and Kedrowski (1983) determined that temperature is not a strong direct limitation to plant growth in the Arctic. Neilson et al. (1972) documented that Sitka spruce needles are capable of photosynthesis at a temperature range of  $-3^{\circ}$  to  $-5^{\circ}\text{C}$  (approximately  $26^{\circ}$  to  $18^{\circ}\text{F}$ ). Hollister et al. (2005), studying tundra plants in situ, found that thawing-degree-day (TDD) temperature totals are a better indicator of phenological development than Julian days. Biogenetic research is revealing that temperatures lower than previously thought can begin a cascade of hormonal and genetic responses that initiate plant growth (Fowler et al. 2001; Wang et al. 2006). Adaptation allows many, if not most, cold-climate plants to continue non-dormant activity at air temperatures below  $0^{\circ}\text{C}$  ( $32^{\circ}\text{F}$ ). A study of wiregrass sedge (*Carex lasiocarpa*) in a south-central New York fen demonstrated that new shoots emerge and grow in late October and November, several weeks after the average date of the first killing frost of the region (October 15th) (Bedford et al. 1988). Shaver and Billings (1977) studied water sedge (*Carex aquatilis*), tundra grass (*Dupontia fischeri*), and tall cottongrass (*Eriophorum angustifolium*) under both laboratory and field conditions. Each species demonstrated root growth at near-freezing temperatures. The adaptive nature of plant responses may vary considerably within the species, depending on microsite, altitude, and year, but overall responses indicate that environmental cues other than temperature control growth process in cold climates.

In temperate and tropic zones, plant growth is more influenced by temperature than in colder regions. Lu et al. (2001) found that the growth of the tropical/subtropical wetland cultivar taro (*Colocasia esculenta*) was governed primarily by temperature. Moisture stress interacted with temperature but had much less effect on growth for this crop.

Because plant adaptations allow many plants to grow at temperatures lower than those outlined in the 1987 Manual, growing season is clearly species specific and not date or event dependent. Biological activity occurs over a considerably longer period than is currently defined by the USACE estimation procedure (Tiner 1999). Tiner (1999) compared growing season

dates (Table 1) based on the 28°F and 32°F air-temperature thresholds allowed by the USACE. The lower-temperature threshold results in a growing season that is two to three weeks shorter than the higher-temperature threshold, and the extreme example in western Oregon shows a difference of almost two months. The data in Table 1 can be compared with phenological data of early spring-blooming wetland and non-wetland plants (Table 2). Although early-blooming species provide a visual clue that plant growth is occurring, growth is species specific and includes a variety of activities such as root and shoot elongation, movement of nutrients and water throughout plant cells, and flowering. Examination of the date of first flower for the wetland species listed in Table 2 demonstrates observable growing activity earlier than the beginning growing season dates in Table 1. Non-visible, internal growing activities must take place prior to visible flowering. Bachelard and Wightman (1974) demonstrate three phases of root activity prior to budburst of balsam poplar (*Populus balsamifera*). Hormone-based processes that create visible plant growth undoubtedly occur in all plant species (Taiz and Zeiger 2002). The National Research Council (1995) is an excellent source of additional research that supports biological activity beyond frost-free dates.

**Table 1. Examples of growing seasons across the U.S., using either 28°F or 32°F at a frequency of more than 5 years in 10. (From Tiner 1999.)**

Location	28°F or Lower		32°F or Lower	
	Last Freeze in Spring*	First Freeze in Fall†	Last Freeze in Spring*	First Freeze in Fall†
Orono, ME	Apr 25	Oct 12	May 9	Sep 29
Boston, MA	Mar 28	Nov 20	Apr 8	Nov 7
Burlington, VT	Apr 29	Oct 16	May 12	Oct 2
Buffalo, NY	Apr 14	Nov 1	Apr 27	Oct 18
Philadelphia, PA	Mar 30	Nov 12	Apr 10	Oct 29
Baltimore, MD	Apr 4	Nov 8	Apr 12	Oct 26
Norfolk, VA	Mar 8	Dec 3	Mar 23	Nov 19
Raleigh, NC	Mar 26	Nov 11	Apr 13	Oct 26
Charleston, SC	Feb 23	Dec 4	Mar 16	Nov 18
Atlanta, GA	Mar 10	Nov 26	Mar 26	Nov 12
Orlando, FL	Jan 20	Jan 12	Jan 31	Jan 8
Birmingham, AL	Mar 14	Nov 15	Mar 30	Nov 6
New Orleans, LA	Feb 3	Dec 21	Feb 21	Dec 7
Little Rock, AR	Mar 7	Nov 20	Mar 22	Nov 9
Memphis, TN	Mar 4	Nov 22	Mar 23	Nov 11
Cincinnati, OH	Apr 3	Nov 2	Apr 19	Oct 20
Chicago, IL	Apr 6	Nov 3	Apr 21	Oct 25
Minneapolis, MN	Apr 19	Oct 14	May 1	Oct 4
Fargo, ND	May 3	Oct 3	May 13	Sep 25
Lincoln, NE	Apr 14	Oct 16	Apr 28	Oct 6
St. Louis, MO	Apr 3	Nov 1	Apr 12	Oct 18
Tulsa, OK	Mar 14	Nov 18	Mar 26	Nov 8
Dallas, TX	Feb 22	Dec 11	Mar 7	Nov 26
Houston, TX	Feb 2	Dec 28	Feb 15	Dec 12
Denver, CO	Apr 21	Oct 16	May 1	Oct 5
Boise, ID	Apr 28	Oct 15	May 10	Oct 5
Albuquerque, NM	Apr 6	Nov 6	Mar 18	Oct 27
Sacramento, CA	Jan 6	Dec 30	Jan 25	Dec 17
Portland, OR	Feb 24	Dec 2	Mar 27	Nov 10

\* Probability of occurring later than this date 5 out of 10 years.

† Probability of occurring earlier than this date 5 out of 10 years.

Source: USDA (U.S. Department of Agriculture) Natural Resources Conservation Service, unpublished data for 1961–1990. For wetland delineations, the former should be used, although the Corps districts have discretion to use the latter in southern states (Williams 1992).



**Table 2. Phenological data on early-blooming wetland and non-wetland species in different parts of the northern conterminous U.S. (From Tiner 1999.)**

Location (Source)	Species	Date of First Flower
Eastern Massachusetts (Debbie Flanders, personal communication, 1998)	<i>Acer rubrum</i>	April 8–14
	<i>Alnus rugosa</i>	April 1–7
	<i>Lindera benzoin</i>	April 15–21
	<i>Salix candida</i>	March 25–31
	<i>S. discolor</i>	April 15–21
	<i>Symplocarpus foetidus</i>	April 8–14
Washington, DC	<i>Acer rubrum</i>	March 11*
	<i>A. saccharinum</i>	February 22*
	<i>Alnus serrulata</i>	March 10*
	<i>Cardamine hirsuta</i>	February 27*
	<i>Corylus americana</i>	March 8*
	<i>Lindera benzoin</i>	March 27*
	<i>Populus grandidentata</i>	March 29*
	<i>Salix discolor</i>	March 15*
	<i>S. sericea</i>	March 31*
	<i>Stellaria media</i>	January 28*
	<i>Symplocarpus foetidus</i>	February 9*
	<i>Taraxacum officinale</i>	February 1*
	<i>Ulmus americana</i>	March 2*
Blue Ridge Mountains, NC (Day and Mark 1977)	<i>Acer rubrum</i>	March 11–16
	<i>Cornus florida</i>	April 15–22
	<i>Quercus prinus</i>	April 15–22
Northeastern Minnesota	<i>Picea glauca</i>	April 29–May 28
	<i>Abies balsamea</i>	April 30–May 8
	<i>Larix laricina</i>	April 25–May 9
	<i>Thuja occidentalis</i>	April 10–May 6
	<i>Ulmus americana</i>	April 25–May 8
	<i>Betula papyrifera</i>	April 2–23
	<i>B. allegheniensis</i>	April 2–May 16
	<i>Acer saccharinum</i>	April 18–30
Kansas (Hulbert 1963)	<i>A. rubrum</i>	April 18–30
	<i>A. saccharinum</i>	January 1–March 23
	<i>Ulmus pumila</i>	February 7–March 26
	<i>Ulmus rubra</i>	February 11–April 12
	<i>Taraxacum officinale</i>	January 1–April 12
	<i>Lamium amplexicaule</i>	January 22–April 25
	<i>Vinca minor</i>	February 3–April 30
Great Basin, NV (Everett et al. 1980)	<i>Hilaria janessii</i>	March 24–April 7†
	<i>Atriplex confertifolia</i>	March 28†
	<i>Oryzopsis hymenoides</i>	March 24–April 2†
	<i>Chrysanthemum viscidiflorus</i>	March 18–24†

\* Mean dates

† Break in dormancy

Note: In southern parts of the U.S., flowering occurs year round, with some species in bloom during winter.

### 2.1.2 Photoperiod

Photoperiodic plant responses complement the plant's seasonal thermoperiodic responses. Photoperiod initiates winter dormancy, whereas temperature conditions primarily determine cessation of dormancy in the spring. The shortened photoperiod is accompanied by the lower temperatures of winter. Release from the dormant state depends on species-specific chilling hours. In temperate climates, the requisite chilling hours are usually met by January or February, but new growth will not begin until the spring temperature warm-up (Wareing 1969). Decreasing photoperiod has been shown to reduce root elongation rates in the tundra grass species *Dupontia fisheri* and the sedges *Carex aquatilis* and *Equisetum angustifolium* (Shaver and Billings 1977). Numerous studies have reported on the role of light in the growth and bud dormancy cycle of temperate-zone woody plants, especially the role of short photoperiod as the dormancy-inducing signal (Garner and Allard 1923; Kramer 1936; Downs and Borthwick 1956; Wareing 1956; Nitsch 1957; Heide 1974; Li et al. 2003). Excellent literature reviews are provided by Romberg (1963), Salisbury and Ross (1992), and Arora et al. (2003).

While the onset of the growing season is easily identifiable from several indicators of biological activity, many physiological, morphological, and climatic factors make the two visible clues of dormancy (deciduous leaf fall and obvious bud set) unreliable indicators of the end of the growing season. For example, drought can induce premature leaf abscission, and woody plant species with fixed-growth, long-shoot-growth patterns exhibit bud set early during the growing season. In addition, dormancy can occur in several degrees of intensity, from pre-dormancy to full dormancy, creating difficulty in visually determining dormancy (Kimmins 2004). Although research based on observable growing activity demonstrates great variety in start dates for the growing season, termination dates cannot reliably be based on visual observations such as leaf fall and bud set (Cooter and Leduc 1995; Chmielewski and Rotzer 2002; Miller et al. 2005).

## 2.2 Above-ground plant response to flooding/soil saturation

The flow of water between soil, plant, and atmosphere plays the largest role in the evolution of a plant species' physiology and hence a plant's ability to survive extreme wet or dry conditions. Obviously, too much or too little water can stress a plant but plants evolve to thrive in harsh

environments. For example, flooded conditions (within limits) are not stressful to wetland plants, just as arid conditions are not stressful to desert plants (Fitter and Hay 2002). Climate, season, soil composition, water availability, stage of plant growth, and evapotranspiration, among other variables, influence the demands of water flow and homeostasis between soil, plant, and atmosphere.

Clearly, water is needed to sustain all living organisms. Each species has unique water needs for optimal development and growth. The foremost source of water for the majority of plants is uptake from the soil through the root system. The availability of soil water affects both the absorption of nutrients by roots and the rate at which the roots elongate (Baver et al. 1972). Root depth is generally a function of soil moisture. Wetland plants have shallow root systems in comparison to their non-wetland counterparts. Soil types also influence root depth but to a lesser degree than moisture. Spring root-elongation intensity, considered an early signal of plant growth, is correlated to temperature and soil water potential. This intensity, however, cannot be fully explained by these two variables because it does not resume in late summer or early fall when temperature and water levels return to conditions equivalent to spring. Joslin et al. (2001) found that soil temperature independently, or combined with soil water potential, was not a significant predictor of root-elongation intensity in a mature upland white oak–chestnut oak forest in Tennessee, suggesting that “phenological programming” (Hendrick and Pregitzer 1996) could explain this phenomenon in mature tree stands.

Wetland plants have adapted to the soil saturation and flooding associated with wetland hydrology, but these extreme conditions have a variety of effects on non-wetland plants. Prolonged soil flooding is injurious to most non-wetland plants and limits their natural distribution to relatively well-drained sites (Parker 1950). Non-wetland plant injury from soil saturation, flooding, or inundation is principally caused by the lack of oxygen, which is required for plant cell division, growth, and the uptake and transport of nutrients. As a soil becomes saturated, the amount of oxygen available to plant tissues below the surface of the soil decreases rapidly because of use by plants and microorganisms. The movement of oxygen from air into water or saturated soil is much slower than in a well-aerated soil and creates an oxygen deficit. The rate of oxygen depletion in a saturated soil depends on a number of factors, but temperature is the most significant and predictable; the higher the temperature, the faster the oxygen is

depleted (Baver et al. 1972). The oxygen level in a saturated soil reaches a point that is harmful to non-wetland plant growth after about 48–96 hours (Singh 1998). The timing of soil saturation during the life cycle of a non-wetland plant greatly impacts the plant's health and survival. Often the effects of inundated soil conditions are not revealed until later in the plant's life cycle.

Kramer (1951) carried out a series of experiments to determine the effects of flooding on plant mortality, foliar discoloration, degree of wilting, and petiole curvature expression. The hypothesis was that damage to flooded plants was the result of decreased water uptake due to root injury. Multiple experiments were carried out on tomato, tobacco, and sunflower, as well as privet (*Ligustrum japonicum*), loblolly pine (*Pinus taeda*), and yellow poplar (*Liriodendron tulipifera*). The lack of water uptake was associated with desiccation but could not be correlated with characteristic effects of flooding, such as stem hypertrophy at the water line or adventitious root development. The range of response to flooding among species was remarkable. Kramer concluded that flood-induced plant damage is complex with several causes, rather than simple interference with water absorption. A two-year study on maize response to root zone saturation of various durations and at different stages of plant growth indicated an adaptive response of maize for saturation survival; however, future generations were compromised by a 50% reduction in numbers of kernels per corn ear compared to a control (Lizaso and Ritchie 1997). Other negative results of root saturation include biomass growth reduction through reduced leaf area expansion, increased leaf senescence, and reduced photosynthesis. Tomato cultivars studied under saturated soil conditions revealed similar results (Bhattarai and Midmore 2005). Fruit yield declined by 24% compared to the control, and blossom end rot increased.

Field observation reveals a natural hierarchy of species distribution based on periodic soil flooding patterns. In the 1950s, scientists began studying the effects of saturated soil on wetland plant growth and development. The driving hypothesis was that wetland plants are so well adapted to wetland hydrology that the hydrology will have minimal negative impact. Over a 10-month period, Hunt (1951) studied the effects of four flooding/drying regimes on shortleaf pine (*Pinus echinata*), loblolly pine, and pond pine (*Pinus serotina*). The expected result was that the pond pine would survive flooding and poor aeration better than the loblolly and shortleaf pine. The

results were surprising. Soil flooding caused very little injury, no significant difference in growth rate between species, and no significant differences in mortality among different treatments and species. The results indicated that pine seedlings are generally resistant to injury caused by flooding and that plant response to flooding is more complex than was expected. Parker (1950) tested the hypothesis that injury to the roots caused by flooding would result in a decrease in transpiration resulting from decreased water absorption. Parker studied loblolly pine (*Pinus taeda*), eastern red cedar (*Juniperus virginiana*), bald cypress (*Taxodium distichum*), white oak (*Quercus alba*), chestnut oak (*Quercus prinus*), red oak (*Quercus borealis* var. *maxima*), overcup oak (*Quercus lyrata*), and dogwood (*Cornus florida*). The experiment was conducted during the spring growing season. Results demonstrated similar reductions in transpiration rate for all species, but other biological responses varied greatly, depending on the species' normal moisture regime. Bald cypress showed outstandingly high transpiration rates in response to flooding. Overcup oak demonstrated the same reduction in transpiration as the other oaks but produced new leaf growth after a few days. The root system of the dogwood suffered severe damage within a week of flooding, but white oak, red oak, and overcup oak survived for several weeks. Overall, the study showed that wetland species do undergo damage under prolonged flooding conditions but are adapted to withstand the flooding conditions for longer periods of time. Additionally, a plant's response to flooding may be distinctly different than its response to soil saturation.

Many studies of wetland plants have examined the effects of flooding on annual growth rate (Kozlowski 1984). More recent papers have reviewed the effect of hydrologic regime on physiological and ecological responses (Blom and Voeselek 1996; Dat et al. 2003) of wetland species. Keeland and Sharitz (1995) studied the growth patterns of swamp tupelo (*Nyssa sylvatica* var. *biflora*), water tupelo (*Nyssa aquatica*), and bald cypress on the Savannah River floodplain of South Carolina. The study found that growing rates of different wetland plant species are affected differently by variations in hydrologic regime. The growing season can vary for different species, and even within species, depending on location along the elevation gradient in a wetland. Any alteration of the "normal" hydrologic regime may result in significant changes in tree growth and long-term ecological dynamics. Seasonally flooded wetlands produce a more vigorous growth rate in bottomland hardwood and swamp forests than in upland,

drained, or permanently flooded sites. This increase in growth is often attributed to nutrient deposits and/or increased soil moisture. When the hydrologic regime varies constantly throughout the growing season, hydrophytic vegetation appears to thrive, possibly by alternating above-ground growth with root system development (Keeland and Sharitz 1997). Gravatt and Kirby (1998) discovered that some bottomland hardwood species increase root carbohydrate concentrations under flooding conditions. This study also found that, during flooding, flood-tolerant species are capable of maintaining a 60–70% photosynthesis rate when compared to unflooded controls, whereas the rate for flood-intolerant species falls to 5–25%.

Tardif and Bergeron (1997) examined the radial growth of black ash (*Fraxinus nigra*) and white cedar (*Thuja occidentalis*) in a boreal forest and compared temperatures of populations at flooded and non-flooded sites; an increase in the depth and duration of flooding led to a decrease in growing season, but ash mean-ring width on unflooded sites was similar to floodplain sites. Black ash and white cedar populations were very similar in radial growth. White cedar thrived in years of bountiful rainfall and cool temperatures during the growing season. A previous study (Ahlgren 1957) showed that white cedar stem growth also increased in response to sharp temperature changes. Water availability during growth and leaf expansion is the dominant factor in radial growth for black ash.

McDermott (1954) evaluated seedling tolerance to soil saturation. A ranking system was developed based on the number of days until mortality. Results showed that continuous saturation produced obvious stunting of growth but no mortality. The species order of most-to-least recovery of wetland bottomland trees is as follows: river birch (*Betula nigra*), red maple, sycamore (*Platanus occidentalis*), American elm (*Ulmus americana*), and winged elm (*Ulmus alata*). Hazel alder seedlings (*Alnus rugosa*) showed accelerated growth with short intervals of saturation but no significant changes caused by sustained saturation. These findings indicate that flooding and saturation do not have consistent effects on plant growth. The inconsistent response between species makes it impossible to create ecological standards that relate soil flooding and saturation to plant growth.

### 2.3 Below-ground plant response to soil temperature

Research and knowledge about root and soil temperature interaction is limited. The study of roots in situ and re-creation of soil thermal regimes in a controlled setting are difficult dynamics that impede research. Soil temperature studies in situ have historically been 1) regionally based direct measurements from a few widely spaced sites over a short time or 2) statistical correlations of soil temperatures to air temperatures and soil characteristics and processes. This creates intrinsic problems in study design. One limiting factor is the inability to provide insight into the freeze–thaw cycle and the short-term insulating effects of winter snowpacks. These temporary events create a complex air–soil temperature relationship that is difficult to measure when following traditional soil temperature protocols. Henry (2007) provided an excellent review of the shortcomings of soil freeze–thaw cycle studies and he suggested improvements.

Plant roots have the same temperature as surrounding soil, and root system expansion is a function of two temperature-dependent processes: growth and development (Kaspar and Bland 1992). As already demonstrated with other biological processes, optimum soil-temperature ranges for root growth differ with species as well as type of root. Primary roots are able to grow over a much broader range of temperatures than branch roots (McMichael and Burke 1998). The temperature for maximum production of root mass is only 5°C for oats (*Avena sativa*), 26°C for corn, 20°C for sunflower (*Helianthus annuus*), 30°C for tomatoes, and 33°C for cotton (*Gossypium hirsutum*) (Glinski and Lipiec 1990). In northern latitudes, plants have evolved to compensate for the effects of low soil temperature. Domisch et al. (2001) found that soils in the northern latitudes and boreal zone have a mean temperature of 10°–12°C, with values ranging from 5° to 20°C in the rooting zone, during the growing season. Evidence shows that root growth starts at a critical soil temperature range that varies from 3° to 20°C by species. Domisch et al. (2001) discovered that bud burst and root elongation of Scots pine (*Pinus sylvestris*) were unaffected by soil temperature. Vapaavouri et al. (1992) and Lyre and Garbe (1995) obtained similar results. Billings et al. (1977) found that “roots and rhizomes of arctic tundra grasses and sedges grow and respire more rapidly under chronically low soil temperatures than roots in other ecosystems.” Schaetzl and Isard (1990) found that “the spatial co-occurrence of thick snow packs and warmer, unfrozen soils suggest possible process linkages between large pulses of infiltrating water

and (1) soil regeneration, (2) groundwater recharge, and (3) release of perennial plants from winter dormancy.”

Soil temperature impacts multiple functions of root systems of temperate species. Low temperatures reduce water and nutrient uptake (Nielsen and Humphries 1966; Nielsen 1974) and decrease hydraulic conductance of root systems (Bolger et al. 1992). Enzymatic activity of root systems increases with increased soil temperatures (Nielsen 1974). Gosselin and Trudel (1986) found that changes in soil temperature can impact root–shoot relationships as well as growth and development of the roots.

## **2.4 Below-ground microbial response to soil temperature**

Temperature and moisture play important roles in determining the rate of biochemical reactions that occur in soil. Thompson and Bell (1998) found that wetter conditions at lower geomorphic positions can lead to a shorter microbial activity season. Rates of microbial activity (as measured by respiration) have been known for decades to be temperature sensitive (Edwards 1975; Schlentner and Van Cleve 1985). As saturated soil temperature increases, microbial activity and soil redox potentials escalate. The extended hydric regime during peak microbial activity essentially determines the creation of hydric soil conditions. In addition to soil temperature, microbial activity is a function of the organic carbon content of the soil (Edwards 1975; Vose and Bolstad 2007). Therefore, anaerobic and reducing conditions will not necessarily occur simultaneously with the saturation conditions. Soil temperature also affects the composition of microbes within the soil. Consequently, the microbial community has been divided according to optimal growth temperatures: 1) psychrophiles ( $0^{\circ}$ – $10^{\circ}$ C); 2) mesophiles ( $10^{\circ}$ – $30^{\circ}$ C); and 3) thermophiles ( $30^{\circ}$ – $65^{\circ}$ C) (Herbert and Codd 1986). As with all natural systems, there is some overlap and extension beyond the termination points of each range, but the divisions provide a practical guide.

Low-temperature environments are divided into two major groups: 1) permanently cold conditions (such as the deep ocean) and 2) periodic fluctuation conditions, including arctic and tundra soils. Arctic and tundra soils can range from  $-88^{\circ}$  to  $+15^{\circ}$ C over relatively short time periods (Weyant 1966). Studies conducted to determine the ecological significance of psychrophilic microorganisms in natural environments have found no evidence of a large winter die-back, and the surviving microbial biomass can even immobilize extra nutrients (Clein and Schimel 1995; Lipson and



Monson 1998; Schmidt et al. 1999). Lipson and Monson (1998) also indicate that the alpine tundra microbial community has a high resistance to freeze–thaw and dry–rewet events, in contrast to studies in other ecosystems. Seasonal studies show that mesophilic and psychrophilic bacteria share dominance based on temperature. A study of heterotrophic bacterial flora of Narragansett Bay, Rhode Island, demonstrated that psychrophilic bacteria become the dominant bacteria at temperatures down to  $-2^{\circ}\text{C}$  during the winter months, and psychrophilic and mesophilic bacteria become dominant during the summer months at  $+23^{\circ}\text{C}$  (Sieburth 1967). It is not clear what effect these alternating patterns of dominance have on the soil reduction process (Herbert and Codd 1986). Depletion of oxygen and the chemical reduction of the nitrogen, iron, and other elements in saturated soil is direct evidence of biological activity occurring in plant roots and soil microbial populations (National Research Council 1995). The depletion of saturated soils is of particular importance to wetland delineation. Soil depletion is impossible without meeting the criteria of “growing season,” i.e., underground microbial and plant biological activity is occurring while the soil is saturated. The inconvenience of measuring this underground activity in the field has allowed the importance of this growing season indicator to be disregarded.

Microbial activity is closely associated with the term “biological zero.” It is important to establish the historic perspective of the use of this term to understand its role in the definition of growing season. The historical perspective in this document is based directly on a literature review of biological zero by Rabenhorst (2005), who showed how its usage has increased in the soil science and wetland science communities.

“Some crop scientists identified the concept of ‘zero vital temperature,’ which had an average value of  $4.4^{\circ}\text{C}$ , but the wide range from which this average was derived leaves one with little doubt that it has little significance as a threshold value and that its similarity to the lower range of mesophyllic microorganisms appears to be accidental. Based upon the investigative efforts of this author, it would seem that the term biological zero was not in published use within the soil or agricultural literature before the 1970s.” (Rabenhorst 2005)

Although the term biological zero was first published in the 1975 edition of *Soil Taxonomy* (Soil Survey Staff 1975), it was not explicitly defined, implying that the reader was already familiar with this concept. The concept falls under the discussion of the aquic moisture regime, which refers to microbial activity for the development of reducing conditions in wet soils.

“The aquic (L. aqua, water) moisture regime implies a reducing regime in a soil that is virtually free of dissolved oxygen because the soil is saturated by ground water or by water in the capillary fringe. An aquic regime must be a reducing one. Some soil horizons, at times, are saturated with water while dissolved oxygen is present, either because the water is moving or because the environment is unfavorable for micro-organisms, for example, if the temperature is  $<1^{\circ}\text{C}$  such a regime is not considered aquic...

...The duration of the period that the soil must be saturated to have an aquic regime is not known. The duration must be at least a few days, because it is implicit in the concept that dissolved oxygen is virtually absent. Because dissolved oxygen is removed from ground water by respiration of micro-organisms, roots and soil fauna, it is also implicit in the concept that the soil temperature is above biological zero ( $5^{\circ}\text{C}$ ) at some time while the soil or the horizon is saturated.” (Soil Survey Staff, as cited in Rabenhorst 2005)

The second edition of *Soil Taxonomy* (Soil Staff Survey 1999) retained the concept of biological zero but stated that “in cold regions, there was biological activity below this threshold.” The term biological zero was first incorporated into wetland literature in *Hydric Soils of the United States* (U.S. Department of Agriculture, Soil Conservation Service 1985) with the glossary definition of growing season as “the portion of the year when soil temperatures are above biological zero in the upper part.” The USACE repeated the definition in the 1987 Manual, defining growing season as “the portion of the year when soil temperatures at 19.7 inches (50 cm) below the soil surface are higher than biological zero ( $5^{\circ}\text{C}$ ) as defined by *Soil Taxonomy*.”

Upper soil temperature is controlled by ambient temperature, soil saturation, and other variables. To minimize these variables and avoid the effects of diurnal air temperature fluctuations, the depth of 50 cm was selected. Because of the lag time between air and soil temperatures at this depth, the 1987 Manual based the estimated growing season on the frost-free period between the last killing frost of spring and the first killing frost of autumn (National Water and Climate Center 1995; Eggers and Reed 2006). Once again, this estimation ties growing season to the traditional agricultural concept of higher plant development. In most instances, research references to biological zero as it relates to growing season cite either the USDA or USACE documents.

Growing season has traditionally been related to higher plant growth, but the important role that soil microbes play in the formation of hydric soils, and consequently wetlands, requires further examination. The primary force behind hydric soil formation is soil microbial activity, rather than the plant activity inherent in the agricultural definition of growing season. Therefore, the wetland growing season is related to the period when soil microbes are active in the upper part of the soil. Research continues to present evidence that this growing activity occurs year round, based on ecological and physiological adaptations of both the microbes and higher plants (Megonigal et al. 1996; Seybold et al. 2002; Burdt et al. 2005). According to Rabenhorst (2005), "...there is no microbial equivalent to leaf or litter fall, and because soil microbes will continue to metabolize (at slower rates) even at very low temperatures, many wetland scientists have essentially discounted the concept of growing season...and, rather, tend to focus on the development of anaerobic conditions."

## **2.5 Above-ground plant response to microbial activity**

The reduced soil conditions initiated by flooding and consequent microbial activity have significant implications for the biological processes of both wetland and non-wetland plants. Many negative effects of soil saturation on plant growth and maturation can be attributed to the increased competition between plants and soil microbes for oxygen. As oxygen is reduced, followed by denitrification and reduction of iron, manganese, and sulfate, the pH and Eh of the soil changes as well. Eh becomes more negative (low redox potential). Well-drained soils have Eh values >400 mV, and flooded soils have been shown to exhibit Eh values as low as -300 mV (Turner and Patrick 1968).

Denitrification of soils is a limiting factor for agricultural crop production. Consequently, irrigation, fertilization, and tillage have all been used with varying success to control denitrification in agricultural soil. Irrigation is the primary factor affecting denitrification; soil texture and drainage controlling aeration are secondary factors (Barton et al. 1999). In natural ecosystems, however, soil nitrate levels appear to be the dominant factor regulating denitrification (Robertson and Tiedje 1984; Davidson and Swank 1987). Flood-induced microbial denitrification in soil decreases the supply of nitrate for plants. As the soil oxygen level is depleted, microbes then begin to extract oxygen from the nitrate ( $\text{NO}_3^-$ ) molecule, and nitrogen is converted to a gaseous form that is lost to the atmosphere (denitrification). The amount lost depends on the soil temperature and the length of soil saturation. Depending on soil texture and composition, the excessive water can leach nitrate beyond the rooting zone of a developing plant, adversely affecting plant nutrient uptake (Gambrell et al. 1991).

Additionally, the natural cycle of freezing and thawing plays an important role in the denitrification rate of natural forest systems by stabilizing the denitrification rate when compared to a wetting and drying cycle alone (Edwards and Killham 1986; Groffman and Tiedje 1989). Soil texture and drainage are correlated with denitrification. As the soil texture becomes finer, the ability to hold water increases, and the soil becomes more easily anaerobic. Groffman and Tiedje (1989) observed a pulse of denitrification in the lower temperatures of just-thawed spring soil, as well as a larger spring pulse that developed after soils warmed to  $5^\circ\text{C}$  and higher.

The distress level of nutrient uptake in response to flooding depends on plant species and soil type. The reduction of N, P, K, and Zn in soils translates to reductions of concentration in leaves, with the N concentration demonstrating the most significant decreases, most likely because N is the first ion to be reduced after oxygen has been depleted. Plant uptake of P is strongly correlated to soil type. Ca and Mg uptake is less altered by flooding than that of N, P, or K (Kozlowski 1984). Flooding causes a functional disequilibrium in the root and shoot communication system, which eventually interrupts photosynthesis. Else et al. (1995) found that the delivery rate of N from roots to shoots of tomatoes flooded for 24 hours was only 7% that of non-flooded plants. Chen et al. (2005) discovered that the wetland invasive species broadleaved pepperweed (*Lepidium latifolium*) responded to flooding conditions with a reduction in N leaf concentration but that the level remained in the optimal range of

crop growth, demonstrating that this wetland species is adapted to flooded conditions. Fe and Mn increased in both leaves and roots in response to flooding. Flooded soils can lead to excessive uptake of  $\text{Fe}^{+2}$  and  $\text{Mn}^{+2}$  during prolonged periods of saturation (Ponnamperuma 1972). The toxicity threshold varies by plant species and other factors. Reduction of soil is a major factor that influences wetland plant survival, growth, and productivity. Indeed, it is the wetland plant species' wide range of tolerance to low soil redox conditions that defines a wetland species. Nonetheless, these soil conditions exert substantial influence on critical biological processes. Hydrophytic vegetation shows a higher threshold of tolerance compared to non-hydrophytic vegetation.

### **3 Current Issues Related to Growing Season Use in Wetland Delineation**

As affirmed in previously cited studies, microbial activity and plant growth occur in a wide range of hydrologic conditions, soil temperatures, and air temperatures. Microbes and many native plants have adaptive responses that allow for non-dormant activity year round in all climates. The soil temperature threshold of biological zero is based on the assumptions that microbial activity is negligible below 5°C, microbial redox reactions cease at this temperature, and spring growth and development of a plant can only begin and be maintained at moderate temperatures. Research shows that soil temperatures greater than 5°C are not needed for the establishment of a growing season. Denitrification has been shown to continue in spite of soil temperatures below 5°C (Myrold 1988; Zak and Grigal 1991; Pinay et al. 1993).

As applied across regional temperate zones, the technical definition of growing season creates issues. Megonigal et al. (1996) studied soils in Louisiana, Mississippi, and South Carolina and determined that many southern and coastal plain soils never fall below 5°C, indicating year-round microbial activity in the soils of the Atlantic and Gulf Coastal Plains Region. Field practice reveals that the most difficult condition of the growing season definition is the required soil temperature threshold of 5°C for inundated or saturated conditions. This threshold is difficult to meet because warm temperatures are poorly correlated with spring water table and/or inundation. In northern latitudes, the greater specific heat of water slows the heating of wet soil when compared to surrounding air, which creates a lag time in meeting the soil temperature requirements. In climates where soil temperatures fall below the required 5°C, hydrology conditions are often no longer present when the soil temperature threshold is met, although soil redox conditions may develop at lower temperatures (Megonigal et al. 1996). An excellent review of the topic of microbial activity at lower soil temperatures can be found in National Research Council (1995). The selection of biological zero (5°C) as a standard is derived from the growing season defined in the traditional agricultural context and is not a valid benchmark for native plant observations (Rabenhorst 2005).

Although hydrology works dynamically with temperature in plant growth processes, temperature triggers plant growth processes in the spring. The adaptive nature of plant responses to temperature may vary considerably within species, depending on microsite, altitude, and year, but overall research indicates that heat sums mainly rouse the growth response in temperate climates. In cold climates, environmental cues play a larger role but act in combination with temperature in initiating the growth process. In both temperate and arctic/alpine climates, multiple species begin growing before the frost-free and/or critical temperature is met. A growing season defined by a frost-free event or air temperatures above  $-2.2^{\circ}\text{C}$  ( $28^{\circ}\text{F}$ ) for native vegetation is not supported by the scientific literature.

Hydric soil is created by a complex hydrologic regime. Predominant hydrophytic vegetation is determined by hydrologic processes as well. The studies cited in this literature review do not support a specific time for hydrology to be present while hydrophytic plants are growing. The growth/dormancy cycle of hydrophytic vegetation does not depend on soil saturation occurring within the arbitrary timeframe recommended by the National Research Council (1995). Tying the delineation of a wetland to the saturation of soil during an artificially time-based growing season is not supported by research.

As stated in the introduction, the National Research Council (1995) suggested that “two general possibilities exist for resolving the problems caused by the use of growing season in the identification of wetlands.

1. Abandon growing season as a constraint on the duration threshold for inundation and saturation and replace it with a system that links duration with temperature.
2. Redefine the growing season by region on the basis of careful scientific study of natural wetland communities and processes.”

In an attempt to develop clarification, the growing season definition has undergone several changes in USACE publications. The use of “frost-free” guidelines has little relevance to native vegetation. The use of biological zero as a guideline does not accurately depict when plants are growing or when microbial processes are advancing hydric soil features (Tiner 1999). The inherent weakness of tying wetland delineation to the 1987 Manual’s definition of the growing season, as it relates to soil temperature and saturation duration, is apparent when reviewing studies of native wetland

plant responses to these factors. Man-made standards are not relevant to native plant growth activity. Essentially, factors influencing hydrophytic plant growth are complex and not limited to soil saturation duration in relation to soil temperature.



## 4 Recommended Solutions and Future Research

Several solutions regarding the use of the growing season definition have been suggested in the scientific literature and are presented below.

Thompson and Bell (1998) suggest a change to the hydric soil definition, proposing “that technical requirements for the duration and frequency of anaerobic conditions be defined to ensure consistency in the specification of field indicators of hydric soils... Currently, rigorous evaluation of proposed field indicators of hydric soils is not possible because there is no uniform basis for comparison.”

Rabenhorst (2005) suggested that, from the standpoint of hydric soils, the idea of a “growing season” must be related to the period when soil microbes are active in the upper part of the soil. Regional temperature and climate create the greatest obstacles in unifying the growing season definition. Soil temperature and plant-growing indicators are directly correlated to ambient temperature and climate. When plant and microbe activity are taken into account, many wetland scientists affirm that the growing season extends throughout the year. The technical standard for hydric soil does not take growing season into consideration (National Technical Committee for Hydric Soil 2000). According to Rabenhorst (2005), in 2003 the National Technical Committee for Hydric Soil (NTCHS) agreed to change the definition of biological zero to read “the soil temperature at a depth of 50 cm (19.7 inches) below which the growth and function of locally adapted plants are negligible.” This change in definition was an attempt to apply the previous definition to northern latitudes. Rabenhorst (2005) suggested that the following issues be considered before accepting the definition:

“First, in temperate regions there appears to be a temperature threshold in the vicinity of 5°C below which the metabolic activity of mesophyllic microbes substantially decreases. One may reason that a comparable threshold exists (at a presumably lower temperature) in colder environs, but this has yet to be demonstrated.

“Second, if such a lower temperature threshold exists for microbes in colder regions, then one must determine how to measure or estimate that temperature. The NTCHS has suggested that this threshold temperature can be estimated at 50 cm at the time when ‘the growth and function of locally adapted plants are negligible.’ Perhaps this is a suitable approach, but it has yet to be demonstrated.

“Third, one must assess the implications of this change for areas with warmer climates. For example, in deciduous woodlands of the Southeastern USA, ‘the function of locally adapted plants’ (trees) will become negligible at the time of leaf fall. If this occurs when the soil temperature is (as it most likely will be) well above 5°C, will biological zero be redefined in these settings to be some warmer temperature (say 80, 100, or 12°C)?”

Burdt et al. (2005) suggested removing the growing season concept entirely or improving the accuracy of the growing season definition, including:

- 1) Using a continuous growing season concept, developing empirical relationships or regression models between air temperature, soil temperature, and hydrologic data for mesic and colder soil temperature regions.
- 2) Determining the effects of surface litter and snowpack >20 cm in mesic and colder regions. Studies should be modeled to replicate Isard and Schaetzl (1995) variables to predict well-drained wetland soil temperatures at 50 cm. If the continuous growing season concept is adopted, then modeling would be unnecessary for mesic regions.
- 3) Following the National Research Council (1995) recommendation that wetland soil depth should be defined at 30 cm rather than 50 cm because of the shallow rooting zone of wetland plants.

Groffman and Hansen (1997) suggested that functional values of wetlands need to be incorporated in delineating a wetland. More research

conducted by region in selected wetland hydrogeomorphic classifications is needed to correlate the above-ground phenology of characteristic species with the presence of wetland hydrology, soil temperature, air temperature, and photoperiod.

Megonigal et al. (1993) found that data that do not support the requirement of evidence of ponding or flooding to classify a site as a wetland, suggesting that the biogeochemical processes that produce redoximorphic features are temperature dependent. “One aspect of the criteria for wetland soils and hydrology...[is] the anaerobic and reducing conditions [that] may develop during the non-growing season. Because palustrine forests in the southeastern USA are flooded mainly during the winter and spring months this criterion deserves further evaluation.” Work is needed on the temperature-response characteristics of key wetland biogeochemical processes that are temperature dependent, both in the field and in the lab.

## 5 Conclusion

The term “growing season” has many definitions. Both the traditional agricultural usage of the frost-free period and the early soil scientists’ concept of biological zero have been included in the federal standards and methods of wetland delineation. The 1987 Manual definition and the NRC technical standard have created problems in consistent application across the U.S. Multiple studies have attempted to address the shortcomings of the definition and offer solutions:

- Thompson and Bell (1998) proposed creating a uniform basis for comparing field indicators of hydric soils.
- Rabenhorst (2005) suggested investigating specific issues related to the 2003 NTCHS change of the definition of biological zero to read “...the soil temperature at a depth of 50 cm (19.7 inches) below which the growth and function of locally adapted plants are negligible.”
- Burdt et al. (2005) suggested doing a literature review of previous research and/or new experimentation to develop empirical relationships or models between air temperature, soil temperature, and hydrologic data. They also suggested conducting more studies of the effects of surface litter and snowpack on soil temperature and microbial behavior.
- Groffman and Hansen (1997) determined that “temporal patterns of denitrification did not fall within conventional wetland delineation guidelines that are based on a ‘growing season.’ Denitrification rates were markedly unresponsive to variation in soil temperature and were not inhibited by temperatures below 5°C (the definition of growing season commonly used in wetland delineation protocols).” Citing Brinson (1993) and Davis (1994), they suggested that the inability of current delineation and classification schemes to incorporate functional values of wetlands is problematic and reinforces the need for distinct systems for functional evaluation of wetlands.
- Meganigal et al. (1993) suggested the need for work on the temperature-response characteristics of key wetland biogeochemical processes that are temperature dependent, both in the field and in the lab.

Each of these suggestions would encounter difficult time, funding, and manpower obstacles to refining the growing season definition and improving wetland delineation standards. Obstacles notwithstanding, the overall body of data described in this literature review demonstrates that the aggregate of wetland ecological factors influencing hydrophytic plant growth points toward the impossibility of a definition applicable for the entire U.S. A definition of growing season for field purposes is not feasible or necessary. The proposed and existing regional supplements address the growing season indicators on a more manageable geographic scale.

Undue emphasis has been placed on the concept of growing season in wetland delineation. Many wetland functions, such as water purification, groundwater recharge, flood control, and erosion reduction, continue year round, independent of plant growing activity, and should be equally valued.

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**14. ABSTRACT**  
The growing season definition in the 1987 U.S. Army Corps of Engineers Wetland Delineation Manual is derived from the soil biological zero temperature concept. Lacking direct information on soil temperatures, minimum air temperature thresholds are used as indicators of the beginning and ending dates for the growing season. The 1987 Manual regional supplements allow for field observations of above-ground plant growth to estimate the growing season period. Since acceptance of the 1987 Manual, the growing season concept has been controversial. Soil biological zero does not apply to large areas of the continental United States, minimum air temperature thresholds appear inconsistent with observations of above- and below-ground biological activity, and photoperiodism and thermoperiodism result in local, regional, and annual variations for determining the growing season period based on plant activity. Also, the belief that wetlands perform ecological functions year-round support the argument that defining the growing season is irrelevant. A literature review of the environmental factors that influence above- and below-ground biological activity is presented. Recommendations are made on the use of the growing season concept to support jurisdictional wetland delineation determinations.

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