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# Identifying Hydric Soils Using α,α′-Dipyridyl Dye

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**PURPOSE:** The application of α,α′-dipyridyl dye (pronounced alpha, alpha di-peeri-dill) provides a reliable and defensible mechanism for documenting the presence of reduced iron in support of hydric soil identification and wetland delineation activities. The α,α′-dipyridyl dye has proven particularly useful for identifying hydric soils in naturally problematic, altered, and disturbed soils. The proper application of paper test strips embedded with α,α′-dipyridyl dye further promotes the use of this technique to improve wetland delineation and management. This technical note summarizes the state of the science related to α,α′-dipyridyl dye and provides practitioner recommendations for applying, documenting, and interpreting α,α′-dipyridyl dye in hydric soil and wetland investigations.

**INTRODUCTION AND BACKGROUND:** Hydric soils are evaluated in conjunction with wetland hydrology and hydrophytic vegetation to identify and delineate wetlands. Hydric soils are defined as soils "that formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part" (Soil Conservation Service 1994, vol. 133). Typically, field indicators of hydric soils are used to document the presence of hydric soils and establish their boundaries on the landscape (USDA-NRCS 2024). The field indicators of hydric soils evaluate the presence of distinct morphologies and characteristics resulting from anaerobic conditions including carbon accumulation (e.g., dark soils) and the transformation and relocation of iron, manganese, and sulfur (e.g., gray soils, redoximorphic features, rotten egg odor) (Figures 1 and 2).

However, some naturally problematic and anthropogenically disturbed or altered soils (collectively known as difficult soil situations) lack the distinct hydric soil morphologies and chemical reactions associated with wetlands for a variety of reasons. For example, soils subject to the placement of fill materials or excavation, recently formed wetlands, seasonally saturated areas, shallow soils, some Vertisols, and soils with high chroma (e.g., red) or dark parent materials may not exhibit the typical hydromorphological features addressed using the field indicators of hydric soils (Vepraskas and Sprecher 1997; USACE 2012). In response, strategies to identify problematic and disturbed hydric soils have been developed, including the installation and monitoring of water table wells and platinum electrodes, the application of chemical dyes, and other techniques (Berkowitz et al. 2021). Additionally, these strategies can be used to evaluate the current functional status of a hydric soil, imply the delivery of hydric soil and wetland functions such as denitrification and carbon sequestration, and can document the success of wetland restoration/mitigation projects.

**Figure 1. The redox ladder indicates when anaerobic conditions are established and the sequential transformation of redox active elements via microbial organic matter respiration. The general zone of α,α′-dipyridyl dye reaction coincides with the chemical reduction of iron. (Adapted from Duball et al. 2020. CC BY-NC-ND 4.0.)**

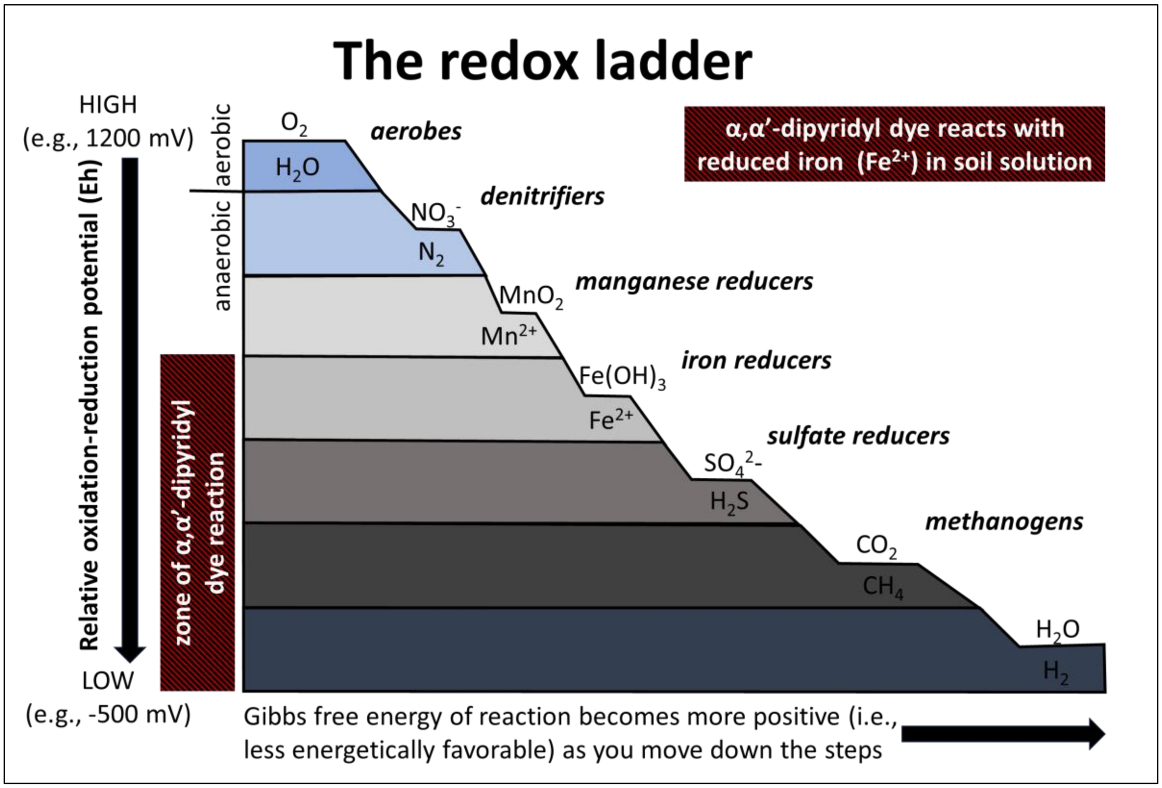
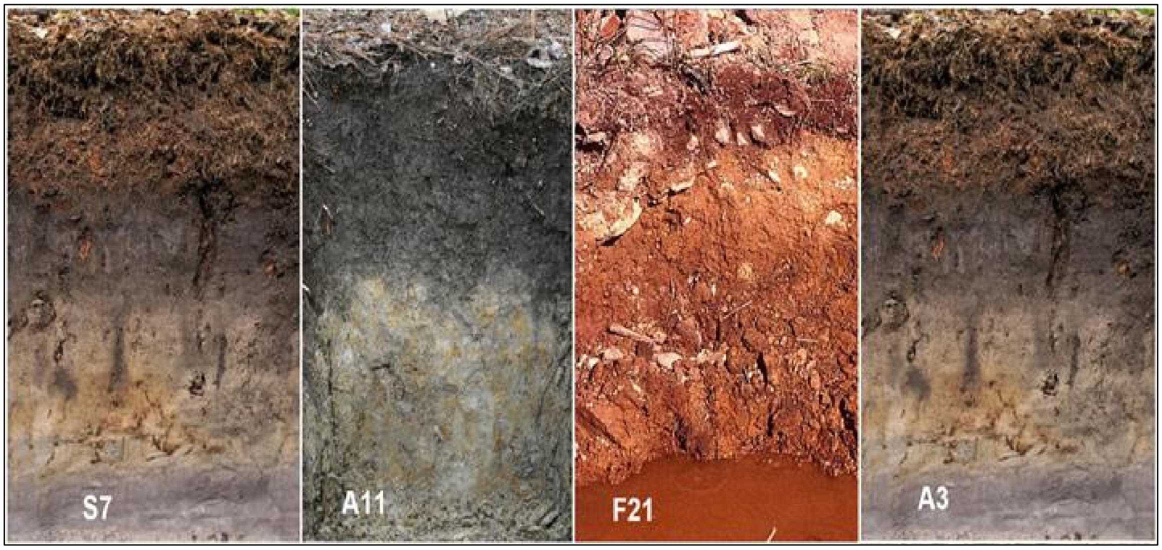


**Figure 2. The field indicators of hydric soils are used to identify and delineate hydric soils based on morphological features that form in response to anaerobic conditions. Representative examples include S7—Dark Surface, A11—Depleted Below Dark Surface, F21—Red Parent Material, and A3—Black Histic. (Image adapted from USDA-NRCS 2024. Public domain.)**



Chemical dyes, most commonly α,α′-dipyridyl dye, provide an easy and defensible way to identify anaerobic conditions and hydric soils, address many difficult hydric soil scenarios, and evaluate the current functional status of a hydric soil. In practice, the α,α′-dipyridyl dye is applied to soil and if a colorimetric reaction occurs producing a red or pink color, the presence of reduced iron (and anaerobic conditions) is confirmed and the definition of a hydric soil is met (Figure 3). The development of a positive reaction to dye application results from the presence of reduced iron in soil solution, which is induced by the chemical reduction of insoluble oxidized ferric iron to its soluble reduced state (i.e., $Fe^{2+}$ [ferrous iron]). This transformation occurs in response to the oxidation of soil organic matter by facultative and obligate anaerobic iron reducing soil microorganisms respiring organic matter in saturated soils. The α,α′-dipyridyl dye compound binds with the $Fe^{2+}$ in soil solution, producing the reddish or pink reaction as $Fe^{2+}$ undergoes complexation with the bonded pyridine aromatic rings (Figure 4). Heaney and Davison (1977) showed that the α,α′-dipyridyl reagent reliably distinguished $Fe^{2+}$ from $Fe^{3+}$, and that dye results corresponded well with measurements of the associated concentration of these oxidized and reduced iron species.

**Figure 3. Example of a positive reaction to α,α′-dipyridyl dye, indicated by the development of a red or pink color following application of the dye onto a saturated soil containing $Fe^{2+}$ in soil solution. This example used α,α′-dipyridyl dye test strips.**

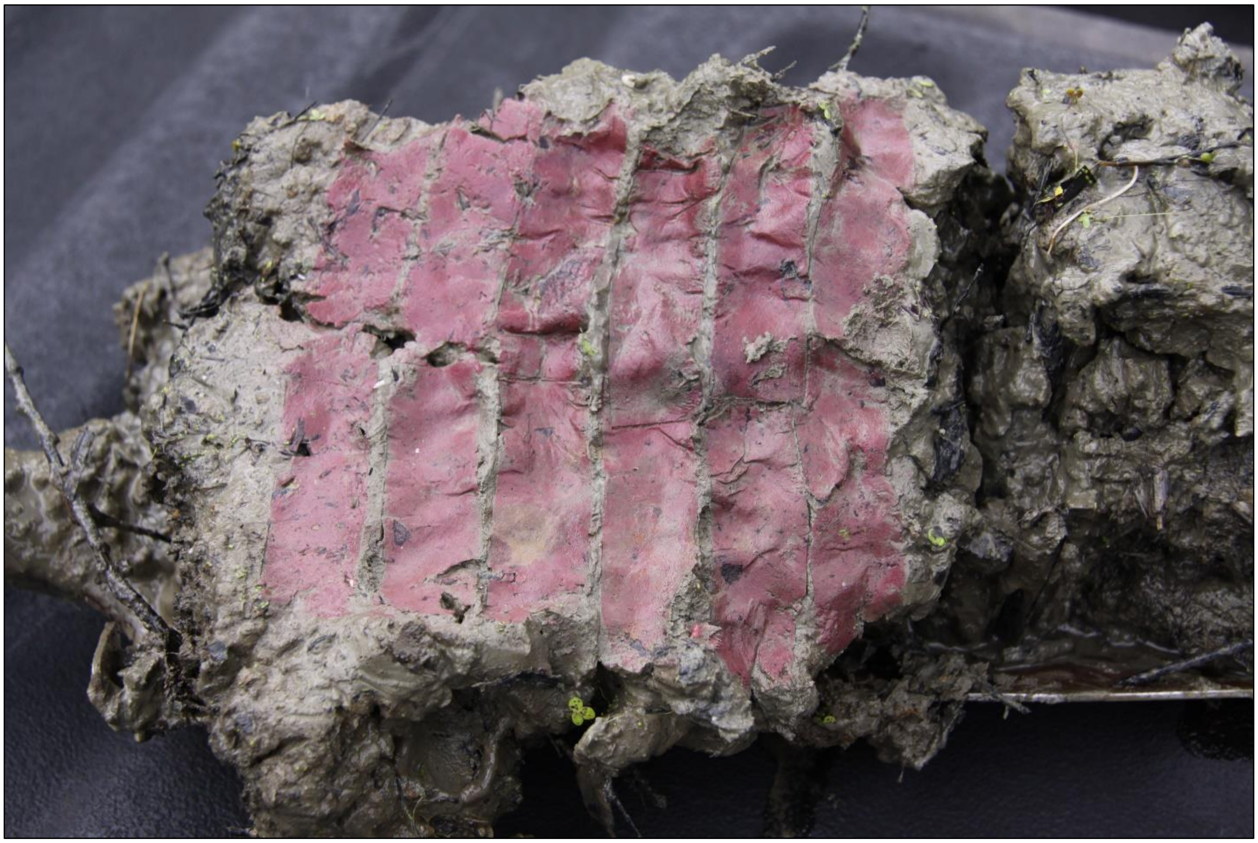
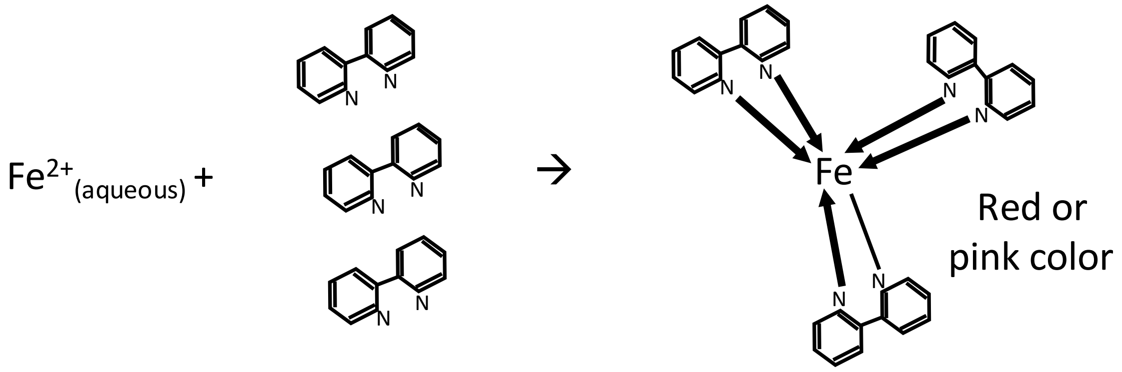


**Figure 4. (1) Chemical equation for iron reduction of a common oxidized iron compound and (2) schematic of ferrous iron complexation with α,α′-dipyridyl dye bonded pyridine aromatic rings resulting in the development of a red or pink color.**

1) Chemical reduction of iron oxide:

$$Fe(OH)_{3(solid)} + e^- + 3H^+ \rightarrow Fe^{2+}_{(aqueous)} + 3H_2O$$

2) Reaction of reduced iron with α,α′-dipyridyl dye:



Several synonyms exist for α,α′-dipyridyl dye, including 2-2′-dipyridyl, 2-2′-bipyridine, bipyridine, and α,α′-bipyridine. However, α,α′-dipyridyl dye (or alpha, alpha-dipyridyl dye) is most commonly used. Additionally, there are other chemical dyes (e.g., 1,10-phenanthroline) that display a colorimetric reaction in the presence of $Fe^{2+}$, but α,α′-dipyridyl dye is most often used and is recommended for application related to hydric soils and wetland delineation (Richardson and Hole 1979; Childs 1981; USACE 2012). Despite the decades-long history of α,α′-dipyridyl dye application in the context of hydric soil identification, questions persist concerning the application of the dye, particularly when nonsoil scientists conduct wetland practitioner activities, including wetland delineation, wetland restoration, and other initiatives.

For many years, α,α′-dipyridyl dye was applied to the soil as a liquid. The liquid dye is formulated by dissolving the chemical compound in a 1 M ammonium acetate solution buffered to a near neutral pH to yield a concentration of 0.2% α,α′-dipyridyl.[*] First, 77 g of ammonium acetate is dissolved into 1 L of distilled water. Then 2 g of α,α′-dipyridyl dye powder is added, and the mixture is stirred until the dye fully dissolves. The solution must also be buffered to a pH of approximately 7.0 using buffer tablets or buffer solution. The pH buffering is required to avoid potential errors associated with photochemical reduction of ferric–organic complexes described in Childs (1981). Care should be taken to avoid touching, ingesting, or introducing α,α′-dipyridyl to

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[*] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

the eyes, and thoroughly wash skin exposed to the chemical with soap and water (See a Material Safety Data Sheet for α,α′-dipyridyl for details).

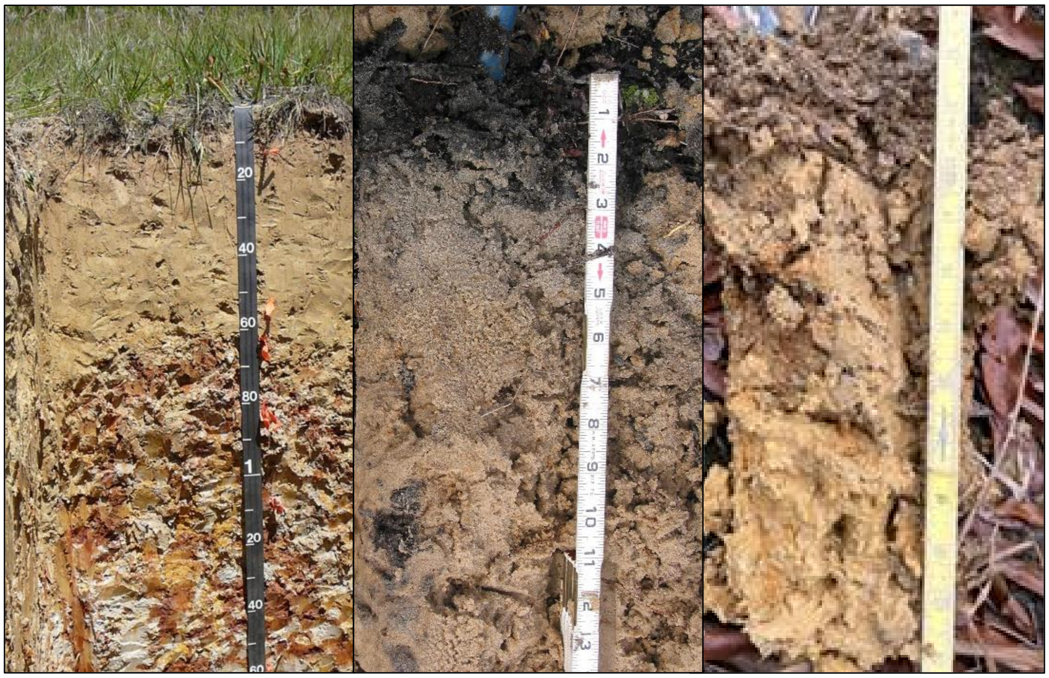
More recently, paper test strips impregnated with α,α′-dipyridyl have become readily available, and represent an affordable and easy approach to dye application. Often sold in boxes that contain 200 strips for a cost of approximately $0.25 per test strip, this represents a significant advancement in the availability and practicality of α,α′-dipyridyl dye for practitioner use. These commercial products are most often advertised as “dipyridyl paper” and are available from a variety of online chemical manufacturing and commercial retailers. The paper test strips were initially manufactured to test for the presence of $Fe^{2+}$ during industrial applications but have proven effective in the field of wetland and hydric soil evaluations.

A study conducted by Berkowitz et al. (2017) demonstrated that liquid and paper test strip formulations delivered similar results, exhibited similar detection limits, and worked well across a broad range of soils from multiple regions. Wetland practitioners generally display a preference for the paper test strips over the liquid dye formulation because (1) no laboratory apparatus or preparation is required, (2) application of the paper test strips does not require special field equipment (e.g., spray bottle, dropper), and (3) some evidence suggests that the paper test strips may be less susceptible to degradation from light or heat, and therefore may be more robust for typical field applications (Berkowitz et al. 2017).

The use of α,α′-dipyridyl dye to identify hydric soils is well established, with studies occurring over several decades and across diverse physiographic regions. For example, Griffin (1991) and Griffin et al. (1992) used the dye to examine wet Alfisols, Mollisols, and Vertisols in Texas; Szogi (1992) and Szogi and Hudnall (1992) used the same method to examine wet Alfisols in Louisiana; Ping et al. (2008) applied the dye to permafrost soils in Alaska; Segal et al. (1995) used the technique in sandy Florida soils; K. Vaughan et al. (2020) applied the approach in serpentine soils in California; and Parker et al. (2010) used the dye on Vertisols in Texas. Further, Berkowitz et al. (2017) applied α,α′-dipyridyl dye to five distinct soil textures (clay, silt, loam, sand, and muck), and reported that the dye performed well across a broad range of soil characteristics including pH, iron content, and organic matter content in soils from several regions.

The use of α,α′-dipyridyl dye has proven particularly effective for identifying hydric soils in problematic situations, in which parent materials or other naturally occurring conditions delay or prevent the formation of field indicators of hydric soils (Figure 5). Examples include evaluations of high chroma soils that failed to meet field indicators of hydric soils in Michigan, where soils with limited organic matter content are subject to frequent wind-blown sediment deposition (Berkowitz and Sallee 2011) and in Alabama, where extensive bioturbation and iron-rich groundwater retard the formation of low chromas (Berkowitz et al. 2014). Additionally, Rossi and Rabenhorst (2015) used α,α′-dipyridyl dye to investigate soils with low chroma parent materials in Maryland, and King et al. (2019) applied the dye in studies of high pH calcareous soils in Wyoming.

**Figure 5. Examples of naturally problematic high chroma soils where α,α′-dipyridyl dye was effectively applied to document the presence of hydric soils. Soils are from (*left* to *right*) Alabama, Michigan, and North Carolina.**



Of particular interest is the use of α,α′-dipyridyl dye in recently formed, altered, or disturbed wetland environments, where field indicators of hydric soils are often absent due to anthropogenic activities. For example, Vepraskas et al. (1999) used the dye to document iron reducing conditions in newly created wetlands in Illinois. Stevens et al. (2000) successfully applied α,α′-dipyridyl dye to identify hydric soils in areas subject to mining disturbances and earth moving activities in Tennessee. The technique has proven useful in areas with altered hydrology, with Hayes and Vepraskas (2000) using it to study hydric soils subject to drainage in North Carolina; R. Vaughan et al. (2008) investigating soils formed in agricultural areas subject to ditching; and Nally (2011) evaluating the effect of dam operations and hydrologic alterations on hydric soils in Texas. Notably, Scott et al. (2024) applied α,α′-dipyridyl dye to verify that the presence of iron reduction in a wetland restoration and mitigation context in Maryland, and Berkowitz and VanZomeren (2020) used the dye to evaluate wetlands restored using dredged sediments in New Jersey, Rhode Island, and Massachusetts. In addition to these published studies, many practitioners have used α,α′-dipyridyl dye when evaluating areas subject to the placement of fill materials and other disturbances, including in support of legal proceedings related to violations of the Clean Water Act and associated regulatory statutes.

The available data highlight the utility of α,α′-dipyridyl dye under a wide variety of scenarios. However, proper application of the dye and informed interpretation of the results are required to ensure the technical accuracy of results.

**APPLYING α,α′-DIPYRIDYL DYE:** In order for α,α′-dipyridyl dye to be used, the soil must be saturated at the time of application and must have remained saturated for a sufficient duration to induce anaerobic conditions and the chemical reduction of oxidized $Fe^{3+}$ to its reduced $Fe^{2+}$ (i.e., ferrous state) (see Figures 1 and 3). Users should not apply the dye to dry soil or attempt to wet the soil prior to application. As a result, the period of α,α′-dipyridyl dye application must coincide with a period of wetland hydrology and reactions to the dye are most likely to reliably occur during the normal wet portion of the growing season. The US Army Corps of Engineers (USACE) Regional Supplements for Wetland Delineation and resources including the Antecedent Precipitation Tool provide guidance for identifying the most appropriate periods for dye application in each area (USACE 2012; Gutenson et al. 2023).

If the soil is unsaturated at the time of sampling, application of α,α′-dipyridyl dye will not induce a reaction. Additionally, water cannot be added to saturate the soil, because sufficient time is required for iron reduction to occur, and for sufficient ferrous iron to accumulate in soil solution to induce a dye reaction (see Figure 1). For example, Berkowitz et al. (2017) reported that anaerobic conditions required between 8 and 32 days to occur across a wide range of soils, and positive reactions to α,α′-dipyridyl dye were observed between 11 and 32 days after soils were saturated.

When saturated soils are encountered, the α,α′-dipyridyl dye should always be applied to the soil sample as soon as it is excavated from the ground. When doing so, a ped of soil should be opened by hand to expose its interior. Care must be taken to avoid placing the dye on surfaces that have come into contact with metal sampling tools, including shovels, soil knives, augers, or other implements that may contain iron.

When using the liquid α,α′-dipyridyl dye, the solution should be applied to the soil surface using a dropper or small spray bottle (Figure 6). In many cases, a positive reaction to the dye is instantaneously observable on the soil surface. However, in some instances, the color becomes visible and intensifies following dye application. The reaction may also be confirmed by dabbing white tissue paper onto the saturated area treated with the dye and evaluating the tissue paper for the presence of a red or pink color. The tissue paper technique is especially effective when evaluating dark soils because the dark colors (low Munsell value and chroma) can mask the response to dye application. Alternatively, a small amount of soil can be placed into a clear vial containing the dye (Figure 7; Childs 1981). While the vial technique is less commonly applied, it has utility in documenting the relative degree of iron reduction across hydrologic or elevation gradients, or in other scenarios where additional data on oxidation-reduction regimes is of interest. The intensity of color development following dye application can be quantified spectrophotometrically or visually, providing a relative measure of iron reduction (Berkowitz et al. 2017).

**Figure 6. Examples of positive reactions to α,α′-dipyridyl dye exposed to both liquid formulation (left side of peds) and paper test strips (right side of peds). Note the range of responses from clearly visible reactions in the *left* image, to faint responses in the *center*, to no detectable reaction in the *right* image.**

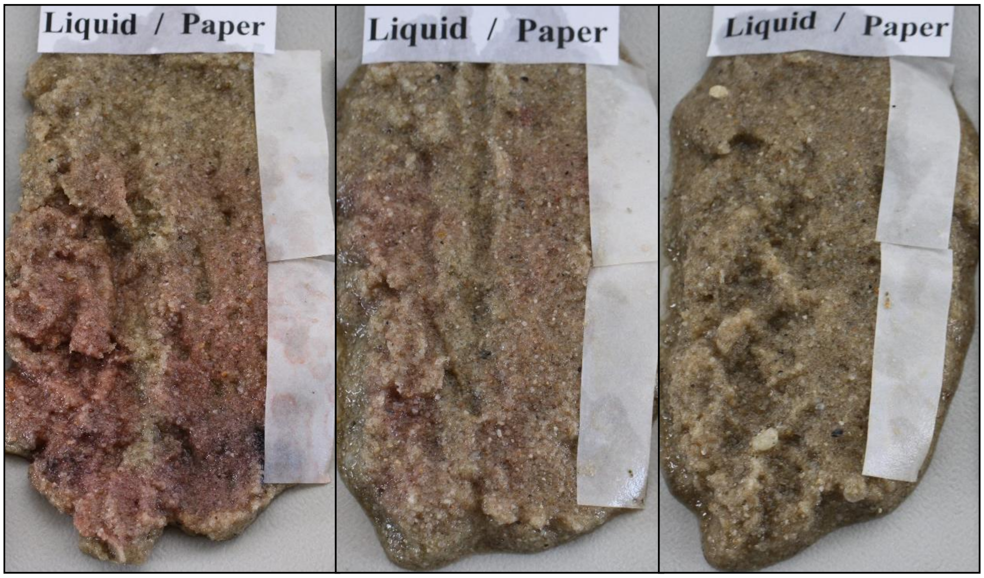
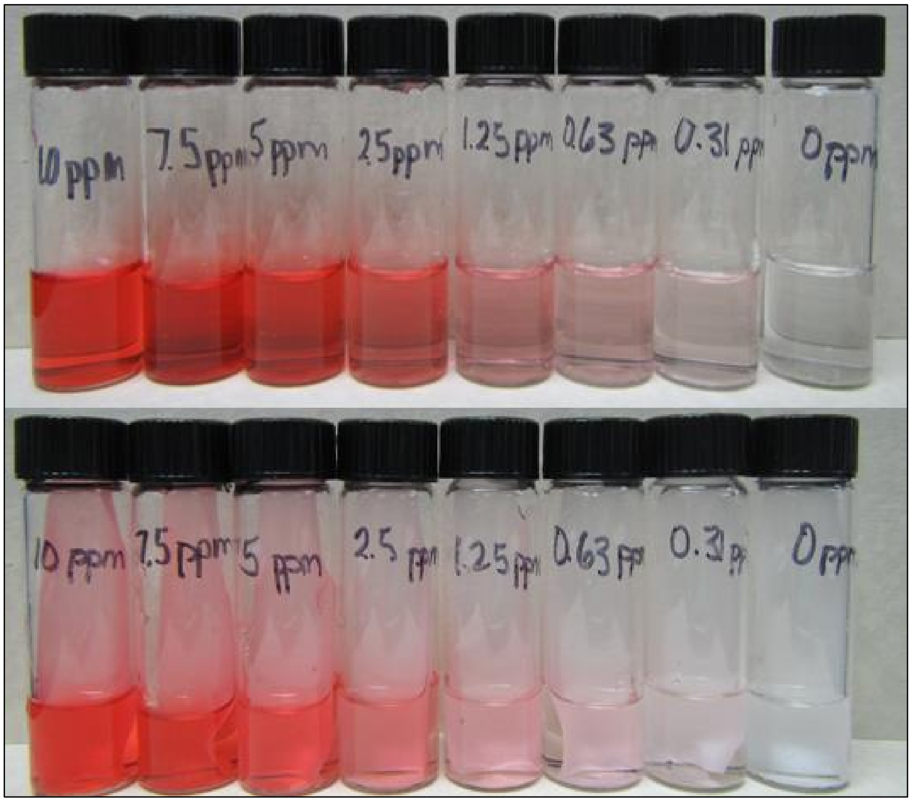


**Figure 7. Examples of α,α′-dipyridyl liquid dye (*top*) and paper test strips (*bottom*) placed in solutions of known dissolved iron concentration.**



When using α,α′-dipyridyl dye embedded in paper test strips, the test strip should be applied to a freshly exposed interior ped surface that has not been in contact with digging implements. Press the paper strip firmly onto the soil surface to ensure maximum contact with the soil solution. In some cases, enclosing the test strip between freshly exposed ped faces provides an effective technique. The presence of hydric soils and anaerobic conditions is confirmed if the development of a red or pink color occurs on the paper test strip or on the soil surface (Figure 8).

**Figure 8. Example of α,α′-dipyridyl dye paper test strip application to a soil containing reduced iron ($Fe^{2+}$) in soil solution. Note that the reaction is clearly visible both on the soil surface and on the paper test strip and that the reaction occurs across more than 60% of the soil layer (Berkowitz et al. 2021).**

The application of paper test strips does not require addition of weak acid or any other solution to the soil surface prior to use. In fact, application of acidic compounds should be avoided because the addition of acid has the potential to dissolve oxidized iron compounds in the soil, resulting in a false positive. For example, some of the commercially available α,α′-dipyridyl dye impregnated test paper kits include instructions to apply a drop of weak acid (greater than pH 2) to the test paper, stating that a red spot or ring will appear in the presence of Fe(II) ions. Recall that the paper test strips were developed for industrial manufacturing applications unrelated to hydric soil evaluations, thus these instructions should be ignored when using α,α′-dipyridyl dye in wetland delineations.

The following illustrates the problem with applying acid solutions during α,α′-dipyridyl dye application in the context of hydric soils. Benchtop studies were performed in triplicate using two saturated soils with circumneutral and alkaline pH values (Table 1). The study used α,α′-dipyridyl dye test strips in the absence of acid and following the addition of 0.1 N hydrochloric (HCl) acid.* Note that the addition of weak acid induced a false positive dye reaction in both soils (results were consistent across all three replicate runs). This observation occurs because alkaline soils exhibit low iron solubility. For example, pH 7.7 soils have iron solubilities near 0.0 mg/L, well below the approximate 0.30 mg/L threshold required to generate a faint positive α,α′-dipyridyl dye reaction (Berkowitz et al. 2017). Acid addition decreases pH and increases iron solubility (Hem and Cropper 1962), allowing $Fe^{2+}$ to enter soil solution and complex with the α,α′-dipyridyl dye to generate a color response. In this scenario, the addition of acid and increased iron solubility results in a false positive. As a result, the addition of acid is discouraged when using chemical dyes to investigate anaerobic conditions in hydric soil and wetland contexts.

**Table 1. The effect of acid addition on α,α′-dipyridyl dye response in two soil orders.**

| | **Soil Order** | |
|---|---|---|
| | **Oxisol** | **Vertisol** |
| pH | 7.97 | 7.39 |
| USDA classification | Moderately alkaline | Neutral / Slightly alkaline |
| Reaction without acid addition | Negative | Negative |
| Reaction following acid addition | False positive | False positive |

Whether using liquid or paper test strip formulations, careful evaluation of the area exposed to α,α′-dipyridyl dye is key to documenting the presence of reduced iron. In soils subject to prolonged periods of saturation that contain ample sources of iron and organic matter, the reaction is often nearly instantaneous and readily observable upon application of the α,α′-dipyridyl dye. However, soils with low iron content, low organic matter content, dark soils, or soils experiencing shorter wetland hydroperiods often display faint responses that require careful examination (see Figure 6). Positive reactions to the dye are typically visible within 30–60 s of application, but may take longer in soils with low amounts of ferrous iron or when cold temperatures are present. Development of red or pink color over periods exceeding a few minutes should not be relied upon to identify iron reduction or hydric soils because the potential for photochemical complexation of the dyes with organic compounds is possible, representing a potential false positive (Childs 1981).

Additionally, previous studies have identified the potential for α,α′-dipyridyl dye to degrade with exposure to light or heat, and in particular the synergistic combination of light and heat (Childs 1981; Berkowitz et al. 2017). As a result, users are encouraged to store α,α′-dipyridyl dye under dark and cool conditions to the maximum extent possible. Operationally, practitioners report reliable results when keeping α,α′-dipyridyl dye and paper test strips in field vests and other locations exposed to hot conditions and other stressors, even across multiple field seasons and sampling campaigns. However, if questions arise related to the reliability of available α,α′-dipyridyl dye, testing samples using soils that are known to have been exposed to prolonged saturated conditions is recommended. Testing dyes on soils in the immediate vicinity of surface waters exhibiting iron films resembling oily sheens that disaggregate into angular platy geometries upon disturbance has also proven effective (Dong et al. 2024). Alternatively, prepared solutions of

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* N = normality.

ferrous ammonium sulfate can be used to effectively test the reliability of α,α′-dipyridyl dyes, as described in Berkowitz et al. (2017).

**INTERPRETING α,α′-DIPYRIDYL DYE REACTIONS:** A positive reaction to α,α′-dipyridyl dye is defined in Berkowitz et al. (2021, 473) as

> A positive reaction to α,α′-dipyridyl dye must occur within 60% or more of a specific soil layer in at least two of three soil samples. The positive dye reaction must occur within a 10-cm-thick [4 in.] layer in the upper 30 cm [12 in.] for most soils, a 6.25-cm-thick [2.5 in.] layer within the upper 12.5 cm [5 in.] in sandy textured soils, or a 5-cm-thick [2 in.] layer within the upper 10 cm [4 in.] in soils that inundate by flooding or ponding.

Soils displaying a positive reaction to α,α′-dipyridyl dye contain reduced iron, and therefore meet the definition of hydric soils. A positive reaction to the dye also indicates that the area is currently functioning as a hydric soil, providing nutrient cycling and other biogeochemical functions that occur in wetland soils. For example, a positive reaction to α,α′-dipyridyl dye indicates that the soil is actively supporting denitrification, providing water quality benefits because the reduction of oxidized nitrogen species occurs prior to the chemical reduction of iron oxides (see Figure 1).

However, care should be used when applying α,α′-dipyridyl dye. False positives can occur if samples are contaminated by coming into direct contact with metal digging implements such as soil knives and shovels that contain iron. As a result, it is imperative that soil peds be excavated by hand or that excavated materials be opened by hand to expose a fresh, uncontaminated surface prior to application of α,α′-dipyridyl dye. The potential contamination of soils by digging implements represents an infrequent and easily avoidable false positive, but care must be used to ensure that any potential contamination is avoided. Additionally, the addition of acidic solutions to the soil can increase iron solubility, leading to false positives, and is therefore strongly discouraged (see Table 1).

False negative reactions can also result in several scenarios. First and as mentioned above, the soil must be saturated at the time of α,α′-dipyridyl dye application. Unsaturated soils will not contain $Fe^{2+}$ and users cannot saturate soils onsite to induce a positive response to α,α′-dipyridyl dye. Second, the soil must be saturated for long enough to (1) induce anaerobic conditions and (2) the chemical reduction of $Fe^{3+}$ at sufficient concentrations to generate a colorimetric response to the dye. As a result, there is a period in which oxygen has been stripped from soil solution (i.e. the onset of anaerobic conditions), denitrification has occurred, and manganese oxide reduction has occurred prior to the formation of $Fe^{2+}$ in soil solution at a concentration that can be detected following dye application (see Figure 1). It is important for practitioners to recognize that for these reasons, a negative reaction to α,α′-dipyridyl dye does not indicate that hydric soils are absent.

**SUMMARY:** Accurate determinations of the presence of hydric soils and wetlands require a comprehensive assessment of site conditions, soil morphology, and other factors as described in USDA-NRCS (2024), USACE (2012), and similar resources. However, the use of α,α′-dipyridyl dye provides a valuable tool to improve the management of hydric soil and wetland resources and is recommended for a variety of applications including wetland delineation, restoration, research, and public education and outreach.

The use of α,α′-dipyridyl dye to identify hydric soils has proven effective in a variety of contexts, including for the identification of hydric soils in support of wetland delineations and when investigating the current functional status of a hydric soil. Additionally, α,α′-dipyridyl dye can inform the management of difficult wetland delineation scenarios, including interpreting areas subject to naturally problematic situations (e.g., red or black parent materials, low levels of organic matter, high pH, and high chroma soils) and anthropogenically disturbed areas (e.g., fill material). When used with care, α,α′-dipyridyl dye provides a valuable tool to quickly identify the presence of reduced iron, and the availability of paper test strips embedded with α,α′-dipyridyl dye promotes the adoption of the dye application to improve the management of wetland resources.

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## REFERENCES

Berkowitz, J. F., S. Page, and C. V. Noble. 2014. “Potential Disconnect between Observations of Hydrophytic Vegetation, Wetland Hydrology Indicators, and Hydric Soils in Unique Pitcher Plant Bog Habitats of the Southern Gulf Coast.” *Southeastern Naturalist* 13 (4): 721–34. https://doi.org/10.1656/058.013.0410.

Berkowitz, J. F., and J. B. Sallee. 2011. “Investigating Problematic Hydric Soils Using Hydrology, IRIS Tubes, Chemistry, and the Hydric Soils Technical Standard.” *Soil Science Society of America Journal* 75 (6): 2379–385. https://doi.org/10.2136/sssaj2011.0040.

Berkowitz, J. F., C. M. VanZomeren. 2020. *Evaluation of Iron Sulfide Soil Formation Following Coastal Marsh Restoration–Observations from Three Case Studies*. ERDC/EL TR-20-1. US Army Engineer Research and Development Center. https://dx.doi.org/10.21079/11681/35275.

Berkowitz, J. F., C. M. VanZomeren, S. J. Currie, and L. Vasilas. 2017. “Application of α,α′-Dipyridyl Dye for Hydric Soil Identification.” *Soil Science Society of America Journal* 81 (3): 654–58. https://doi.org/10.2136/sssaj2016.12.0431.

Berkowitz, J. F., M. J. Vepraskas, K. L. Vaughan, and L. M. Vasilas. 2021. “Development and Application of the Hydric Soil Technical Standard.” *Soil Science Society of America Journal* 85 (3): 469–87. https://doi.org/10.1002/saj2.20202.

Childs, C. W. 1981. “Field Tests for Ferrous Iron and Ferric-Organic Complexes (on Exchange Sites or in Water-Soluble Forms) in Soils.” *Australian Journal of Soil Research* 19:175–80.

Dong, L., M. Chen, C. Liu, Y. Lv, X. Wang, Q. Lei, Y. Fang, and H. Tong. 2024. “Microbe Interactions Drive the Formation of Floating Iron Films in Circumneutral Wetlands.” *Science of the Total Environment* 906: 167711. https://doi.org/10.1016/j.scitotenv.2023.167711.

Duball, C., K. Vaughan, J. F. Berkowitz, M. C. Rabenhorst, and C. M. VanZomeren. 2020. “Iron Monosulfide Identification: Field Techniques to Provide Evidence of Reducing Conditions in Soils.” *Soil Science Society of America Journal* 84 (2): 303–13. https://doi.org/10.1002/saj2.20044.

Griffin, R. W. 1991. “A Study of Aquic Conditions of Seasonally Wet Soils on the Coast Prairie of Texas.” PhD diss., Texas A&M University.

Griffin, R. W., L. P. Wilding, and L. R. Drees. 1992. “Relating Morphological Properties to Wetness Conditions in the Gulf Coast Prairie of Texas.” In *Proceedings of the Eighth International Soil Correlation Meeting (VIII ISCOM): Characterization, Classification, and Utilization of Wet Soils*, edited by J. M. Kimble, 126–35. USDA, Soil Conservation Service, National Soil Survey Center.

Gutenson, J. L., C. O. Hamilton, and J. C. Deters. 2023. *Antecedent Precipitation Tool (APT) Version 2.0: Technical and User Guide*. ERDC/TN WRAP-23-2. US Army Engineer Research and Development Center. http://dx.doi.org/10.21079/11681/47189.

Hayes, W. A., and M. J. Vepraskas. 2000. “Morphological Changes in Soils Produced When Hydrology is Altered by Ditching.” *Soil Science Society of America Journal* 64 (5): 1893–904. https://doi.org/10.2136/sssaj2000.6451893x.

Heaney, S. I., and W. Davison. 1977. “The Determination of Ferrous Iron in Natural Waters with 2,2′ Bipyridyl.” *Limnology and Oceanography* 22 (4): 753–60. https://doi.org/10.4319/lo.1977.22.4.0753.

Hem, J. D., and W. H. Cropper. 1962. “Survey of Ferrous-Ferric Chemical Equilibria and Redox Potentials.” In *Chemistry of Iron in Natural Water*, 1–31. US Geological Survey Water-Supply Paper 1459. US Government Printing Office.

King, M., K. L. Vaughan, K. Clause, and D. Mattke. 2019. “Limitations to Redoximorphic Feature Development in Highly Calcareous Hydric Soils.” *Soil Science Society of America Journal* 83 (5): 1585–594. https://doi.org/10.2136/sssaj2019.04.0108.

Nally, D. D. 2011. “Response of Wetland Soils to Flow Alterations in the Sabine River below Toledo Bend Dam for the Texas Instream Flows Program.” Senior scholars thesis, Texas A&M University. https://hdl.handle.net/1969.1/148769.

Parker, A. F., P. R. Owens, Z. Libohova, X. B. Wu, L. P. Wilding, and S. R. Archer. 2010. “Use of Terrain Attributes as a Tool to Explore the Interaction of Vertic Soils and Surface Hydrology in South Texas Playa Wetland Systems.” *Journal of Arid Environments* 74 (11): 1487–493. https://doi.org/10.1016/j.jaridenv.2010.06.006.

Ping, C. L., G. J. Michaelson, J. M. Kimble, V. E. Romanovsky, Y. L. Shur, D. K. Swanson, and D. A. Walker. 2008. “Cryogenesis and Soil Formation Along a Bioclimate Gradient in Arctic North America.” *Journal of Geophysical Research: Biogeosciences* 113 (G3): S12. https://doi.org/10.1029/2008JG000744.

Richardson, J. L., and F. D. Hole. 1979. “Mottling and Iron Distribution in a Glossoboralf-Haplaquoll Hydrosequence on a Glacial Moraine in Northwestern Wisconsin.” *Soil Science Society of America Journal* 43 (3): 552–58. https://doi.org/10.2136/sssaj1979.03615995004300030024x.

Rossi, A. M., and M. C. Rabenhorst. 2015. “Hydric Soil Field Indicators for Use in Mid-Atlantic Barrier Island Landscapes.” *Soil Science Society of America Journal* 79 (1): 328–42. https://doi.org/10.2136/sssaj2014.08.0317.

Scott, B., A. H. Baldwin, and S. A. Yarwood. 2024. “Consequences of Organic Matter Amendments for Methane Emissions and Soil and Vegetation Development in a Restored Wetland.” Wetlands Ecology and Management 32 (2): 171–90. https://doi.org/10.1007/s11273-023-09967-8.

Segal, D. S., S. W. Sprecher, and F. C. Watts. 1995. *Relationships Between Hydric Soil Indicators and Wetland Hydrology for Sandy Soils in Florida*. Wetlands Research Program Technical Report WRP-DE-7. US Army Corps of Engineers Waterways Experiment Station. https://hdl.handle.net/11681/6518.

Soil Conservation Service. 1994. “Changes in Hydric Soils of the United States.” Federal Register 59, 133. https://www.federalregister.gov/d/94-16835.

Stevens, V. C., J. T. Ammons, J. L. Branson, T. E. Cook, and D. J. Inman. 2000. “Chemical and Physical Characteristics of Anthropogenic Hydric Soils on Mine Tailings in the Copper Basin, Tennessee.” In *Proceedings America Society of Mining and Reclamation*, 537–45. https://doi.org/10.21000/JASMR00010537.

Szogi, A. A. 1992. “A Study on the Aquic Conditions of Two Natraqualfs in the Coastal Plain of Louisiana.” PhD diss, Louisiana State University and Agricultural & Mechanical College. https://doi.org/10.31390/gradschool_disstheses.5470.

Szogi, A. A., and W. H. Hudnall. 1992. “Classification of Soils in Louisiana according to “Endoaquic” and “Epiaquic” Concepts.” In *Proceedings of the Eighth International Soil Correlation Meeting (VIII ISCOM): Characterization, Classification, and Utilization of Wet Soils*, edited by J. M. Kimble, 271–78. USDA, Soil Conservation Service, National Soil Survey Center.

USACE (United States Army Corps of Engineers). 2012. *Regional Supplement to the Corps of Engineers Wetland Delineation Manual: Northcentral and Northeast Region (Version 2.0)*. ERDC/EL TR-12-1. US Army Engineer Research and Development Center. https://hdl.handle.net/11681/10107.

USDA-NRCS (United States Department of Agriculture–Natural Resources Conservation Service). 2024. *Field Indicators of Hydric Soils in the United States: A Guide for Identifying and Delineating Hydric Soils, Version 9.0*. USDA-NRCS, in cooperation with the National Technical Committee for Hydric Soils. https://www.nrcs.usda.gov/sites/default/files/2025-04/Field-Indicators-of-Hydric-Soils-in-the-United-States-Version-9_0.pdf.

Vaughan, K. L., J. DeMoss, T. Cullum-Muyres, and A. Diaz. 2020. “Serpentine Parent Materials Lead to the Formation of Atypical Hydric Soils.” *Soil Science Society of America Journal* 84 (4): 1342–352. https://doi.org/10.1002/saj2.20090.

Vaughan, R. E., B. A. Needelman, P. J. A. Kleinman, and M. C. Rabenhorst. 2008. “Morphology and Characterization of Ditch Soils at an Atlantic Coastal Plain Farm.” *Soil Science Society of America Journal* 72 (3): 660–69. https://doi.org/10.2136/sssaj2006.0102.

Vepraskas, M. J., J. L. Richardson, J. P. Tandarich, and S. J. Teets. 1999. “Dynamics of Hydric Soil Formation across the Edge of a Created Deep Marsh.” *Wetlands* 19 (1): 78–89. https://doi.org/10.1007/BF03161736.

Vepraskas, M. J., and S. W. Sprecher. 1997. “Overview of Aquic Conditions and Hydric Soils.” In *Aquic Conditions and Hydric Soils: The Problem Soils*, edited by M. J. Vepraskas and S. W. Sprecher, 1–22. Soil Science Society of America Press. https://doi.org/10.2136/sssaspecpub50.c1.