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Soil Survey Technical Note 430-SS-11 Acid Sulfate Soils in the Coastal and Subaqueous Environment

Purpose

This technical note defines acid sulfate soils and hypersulfidic soil materials and describes the formation, locations, impacts, treatment and management, and identification of these soils. The detailed procedures for testing and classifying these soils are provided in the Keys to Soil Taxonomy,¹ Soil Survey Field and Laboratory Methods Manual,² and Field Book for Describing and Sampling Soils.³

Acid Sulfate Soils

Acid sulfate (AS) soils form under reducing conditions with sulfide minerals, predominately pyrite (FeS₂) and other iron sulfides. AS soils are soils in which sulfuric acid either will be produced, is being produced, or has been produced in quantities that have lasting effects on soil properties.⁴

AS soils occur in all climatic zones, but the majority occur in coastal areas. The extent of such soils covers over 170,000 km² throughout the world.⁵ Due to the abundance of sulfate in marine environments, sulfide-rich soils are common in coastal and estuarine subaqueous and salt marsh soils. When sulfide-rich soils are exposed to an oxidized environment (such as through dredging or draining), the sulfide minerals oxidizes, creating sulfuric acid in a process known as sulfuricization. The sulfuric acid can drastically lower pH (in some cases to less than 4.0), resulting in a highly acidic soil that can pose severe environmental risks.⁶

¹ Soil Survey Staff, *Keys to Soil Taxonomy* (2022).

² Soil Survey Staff, *Soil Survey Field and Laboratory Methods Manual*, Soil Survey Investigations Report No. 51, [Version 2.0](#) (Rebecca Burt & Soil Survey Staff, eds., 2014).

³ Philip J. Schoeneberger, et al., *Field Book for Describing and Sampling Soils, Version 3.0* (2012).

⁴ L. J. Pons, *Outline of the Genesis, Characteristics, Classifications and Improvement of Acid Sulphate Soils*, 18, Proc. of the Int'l Symp. on Acid Sulphate Soils 3, 3–27 (1973).

⁵ Tapio Sutela & Teppo Vehanen, *The Effects of Acidity and Aluminum Leached from Acid-Sulphate Soils on Riverine Fish Assemblages*, 22 Boreal Env't Research 385, 385–391 (2017).

⁶ Delvin S. Fanning & Mary C. B. Fanning, *Soil Morphology, Genesis, and Classification* (1991); Delvin S. Fanning, et al., *Historical Developments in the Understanding of Acid Sulfate Soils*, 308 *Geoderma* 191, 191–206

There are three types of AS soils: potential, active, and postactive. **Potential** acid sulfate soils (PASS) refer to soils formed in saturated anaerobic conditions containing high levels of hypersulfidic materials (defined later in this technical note). Because these soils are saturated and strongly biochemically reducing, the field pH is generally greater than or equal to 4.0.⁷ **Active** acid sulfate soils (AASS) have a sulfuric horizon and are highly acidic due to oxidation of hypersulfidic materials. **Postactive** acid sulfate soils (PAASS) are AS soils in which weathering and pedogenesis have reached a stage where sulfide minerals are no longer present near the surface and pH has risen above 4.0.⁸ Both AASS and PASS often contain the mineral jarosite ($KFe_3(SO_4)_2(OH)_6$) as evidence of acid sulfate weathering. The presence of jarosite is considered evidence of sulfuricization in soil development.

The term “hypersulfidic materials” will replace “sulfidic materials” in National Cooperative Soil Survey activities. Hypersulfidic materials carry the same definition as sulfidic materials as defined in the 13th edition of the Keys to Soil Taxonomy (also defined later in this technical report).⁹ The transition to the term “hypersulfidic materials” is consistent with international terminology of sulfide-bearing soil materials, including the Australian system¹⁰ and the World Reference Base for Soil Resources.¹¹

Formation

PASS result from the formation and accumulation of sulfide minerals (mainly iron sulfides) through a process known as sulfidization.¹² This process occurs most frequently in coastal or estuarine soil environments where large quantities of sulfate are available from seawater and where reactive iron is available. Landforms and environments where sulfidization commonly occurs are coastal flood plains, tidal marshes, estuarine rivers and creeks, deltas, coastal flats, backswamps, coastal lagoons, bays, coves, and mangrove swamps.¹³

PASS can also form in areas where saltwater intrusion introduces sulfates into previously nonsaline soils. The conditions for sulfidization or sulfate reduction to sulfide include: 1) a sulfate

(2017); Christine M. Van Zomeren, et al., [Acid Sulfate Soils in Coastal Environments: A Review of Basic Concepts and Implications for Restoration](#) (2020).

⁷ South Australian Coast Protection Board, [Coastline—A Strategy for Implementing CPB Policies on Coastal Acid Sulfate Soils in South Australia](#) (2003).

⁸ Delvin S. Fanning, *Acid Sulfate Soils*, in Encyclopedia of Environmental Management 26, 26–28 (Sven E. Jorgensen ed., 2012); Delvin S. Fanning, et al., [Historical Developments in the Understanding of Acid Sulfate Soils](#), 308 *Geoderma* 191, 191–206 (2017).

⁹ See *supra* note 1.

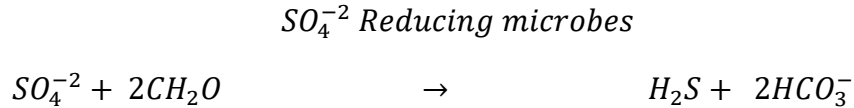
¹⁰ Raymond F. Isbell & Nat'l Comm. on Soil and Terrain, [The Australian Soil Classification](#) (3rd ed., 2021).

¹¹ Barret M. Wessel & Martin C. Rabenhorst, [Identification of Sulfidic Materials in the Rhode River Subestuary of Chesapeake Bay](#), 308 *Geoderma* 215, 215–225 (2017).

¹² Delvin S. Fanning & Mary C. B. Fanning, *Soil Morphology, Genesis, and Classification* (1991); Delvin S. Fanning, et al., [Historical Developments in the Understanding of Acid Sulfate Soils](#), 308 *Geoderma* 191, 191–206 (2017).

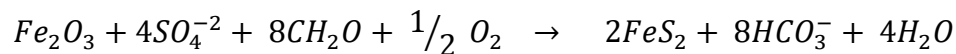
¹³ Bo B. Jørgensen, [The Sulfur Cycle of a Coastal Marine Sediment \(Limfjorden, Denmark\)](#), 22 *Limnology and Oceanography* 814, 814–831 (1977); John W. Day, Jr., et al., *Estuarine Ecology* (1989).

source (e.g., sea water), 2) presence of sulfate-reducing bacteria, 3) a carbon (C) energy source for microorganisms (e.g., detrital organic matter), and 4) an anaerobic and strongly biochemically reducing environment. The basic reaction is:

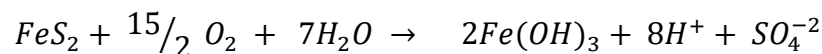


Upon oxygen depletion in an anaerobic environment, other oxidized species (e^- acceptors) are reduced as the environment becomes increasingly biochemically reducing. In these oxygen-depleted environments, sulfate-reducing bacteria obtain energy by oxidizing organic compounds while biochemically reducing sulfur in sulfate (S^{6+}) to sulfide (S^{2-}).¹⁴

Sulfate-reducing bacteria are ubiquitous in these reducing environments and mediate many of the sulfur transformations. Accordingly, sulfate (SO_4^{2-}) is reduced into sulfide (S^{2-}), and iron is reduced from ferric (Fe^{3+}) form in oxide minerals to soluble ferrous (Fe^{2+}) form. These usually combine to form iron disulfide (FeS_2 , known as pyrite) or iron monosulfide (FeS), but may also form a range of iron sulfide minerals, including mackinawite (FeS_m), greigite (Fe_3S_4), and pyrite (FeS_2).¹⁵ The basic reaction of how pyrite is formed is:



When biochemically reducing conditions are maintained in the soil, sulfide minerals remain chemically stable and are considered PASS. If PASS are exposed to oxidized conditions by drainage or other exposure, sulfuricization occurs and forms sulfuric acid. Through sulfuricization, PASS transforms into AASS, as follows:



AASS are highly acidic and may contain a sulfuric horizon (defined in "Identification"). When weathering and pedogenesis have advanced to a stage where sulfide minerals are no longer present and the pH has increased above 4.0, the soils are considered PAASS.¹⁶

¹⁴ M. B. Goldhaber, *Sulfur-Rich Sediments*, in *Treatise on Geochemistry 257*, 257–288 (Heinrich D. Holland & Karl K. Turekian eds., 2003); Dennis Enning & Julia Garrelfs, *Corrosion of Iron by Sulfate-Reducing Bacteria: New Views of an Old Problem*, 80 *Applied Environmental Microbiology* (2014); Kenneth Wasmund, et al., *The Life Sulfuric: Microbial Ecology of Sulfur Cycling in Marine Sediments*, 9 *Environmental Microbiology Reports* 323, 323–344 (2017).

¹⁵ John W. Morse & Jeffrey C. Cornwell, *Analysis and Distribution of Iron Sulfide Minerals in Recent Anoxic Marine Sediments*, 22 *Marine Chemistry* 55, 55–69 (1987); David Rickard & George W. Luther, *Chemistry of Iron Sulfides*, 107 *Chemical Reviews* 514, 514–562 (2007); Tanabhatsakorn Sukitprapanon, et al., *A Comparison of Potential, Active and Post-Active Acid Sulfate Soils in Thailand*, 7 *Geoderma* 346, 346–356 (2016).

¹⁶ Delvin S. Fanning, *Acid Sulfate Soils*, in *Encyclopedia of Environmental Management* 26, 26–28 (Sven E. Jorgensen ed., 2012); Tanabhatsakorn Sukitprapanon, et al., *A Comparison of Potential, Active and Post-Active Acid Sulfate Soils in Thailand*, 7 *Geoderma* 346, 346–356 (2016); Commonwealth of Aust'l, *National Acid Sulfate Soils*

Locations

Soil materials rich in organic matter and iron monosulfides can be highly fluid and are sometimes referred to as monosulfidic black ooze (MBO).¹⁷ MBOs are black (mainly due to the strong black pigmentation of FeS), oily in appearance, and often have a high organic matter content. They can form thick accumulations within PASS landscapes.

PASS commonly occur in coastal environments where there is an abundance of sulfate salts from seawater, and the soils remain in an anaerobic state. A hydrogen sulfide gas odor is often present in these environments, indicating a highly reducing environment where sulfidization occurs and hypersulfidic materials form.¹⁸ AASS are most common in coastal regions but may occur in inland waterways, wetlands, drainage channels, saline seepage areas, and sometimes in uplands derived from sulfidic coastal plain sediments.¹⁹ Signs of AASS include orange-brown water and soil, oil-like slicks, subsurface MBOs, salinity or salt crusts, and vegetation dieback or shifts to acid-tolerant species.²⁰

AASS may form naturally or through human activities that alter hydrologic regimes and expose hypersulfidic materials. Anthropogenic activities, such as dam installation, drainage, water control, mining, and land-clearing, can alter hydrology and enhance oxidation, resulting in AASS formation. Dredging activities commonly expose PASS to oxidation. Other activities can lead to waterlogging and development of oxygen-depleted conditions. These conditions, combined with sulfate sources, may lead to sulfidization and the development of PASS.

Thin layer placement for marsh restoration is a process in which subaqueous soil materials are placed over salt marsh environments to maintain marsh elevation as sea level rises. However, if the layer of soil is too thick, then it may undergo exposure (drying), causing PASS source materials to experience oxidation and produce AASS conditions, which can inhibit vegetation reestablishment in marsh restoration or enhancement projects.²¹

Impacts

The formation of AASS has an enduring and complex effect on the soil and surrounding environment. For every mole of pyrite (FeS₂) that is oxidized, 2 moles of sulfuric acid are

Guidance: National Acid Sulfate Soils Identification and Laboratory Methods Manual (2018); Amanda Lindgren, et al., *Acid Sulfate Soils and Their Impact on Surface Water Quality on the Swedish West Coast*, 40 Journal of Hydrology: Regional Studies 101019 (2022).

¹⁷ Diane M. Fyfe, et al., *Oxidation Pathways of Monosulfidic Black Ooze*, in Proceedings of the 18th World Cong. of Soil Science, Philadelphia, PA, 9–15 July (2006).

¹⁸ Robert G. Darmody & Del S. Fanning, *Whiffing Sulfur Levels of Tidal Marsh Soils*, 18 Soil Horizons 16, 16–17 (1977).

¹⁹ Chelsea E. Duball, et al., *Iron Monosulfide Identification: Field Techniques to Provide Evidence of Reducing Conditions*, 84 Soil Science Society of America Journal, 303, 303–313 (2020).

²⁰ Dep't of Sustainability, Environment, Water, Population and Communities, *Inland Acid Sulfate Soil and Water Quality*, (Parliament of Aust'l, 2012).

²¹ Jacob F. Berkowitz, et al., *Rapid Formation of Iron Sulfides Alters Soil Morphology and Chemistry Following Simulated Marsh Restoration*, 351 Geoderma 76, 76–84 (2019).

produced. The pH, which is normally near neutral before drainage or exposure, can decrease below 3.0.²² The decrease in soil pH significantly enhances the solubility and mobility of metals (e.g., Al, Fe, Zn, Ni, and Cu), which can have multiple deleterious effects on the surrounding environment.²³ In some coastal environments, calcareous materials may neutralize the acidity generated during oxidation of sulfides.²⁴

The extreme acidity produced by these AASS conditions can damage vegetation, resulting in increased erosion and runoff. The increased mobility of metals and ecological impacts of acidification can severely impact agricultural crops as well as terrestrial and aquatic environments, harming aquatic plants and wildlife. High concentrations of aluminum and iron have been shown to cause damage to fish skin and gills, increase the prevalence of disease, and contribute to the development of harmful filamentous algal blooms.²⁵

Prolonged exposure of AASS soils can result in soil subsidence as organic materials are oxidized. In areas where peat topsoil is oxidized through drainage, soils have been shown to shrink as much as 50 percent, causing significant land subsidence.²⁶

AASS can cause structural damage and impact human health. Damage to infrastructure can result from corrosion of concrete, iron, steel, and aluminum. Iron oxide formation can cause rust-colored slimes and stains, block drainage systems, and smother aquatic plants. The mobilization of metals, such as aluminum, iron, and arsenic, can impact drinking water supplies.²⁷

Treatment and Management

The best option for managing acid sulfate soils is to prevent the disturbance of hypersulfidic materials. Ideally, PASS should be identified and then the area should not be disturbed by development or used for marsh nourishment projects. PASS left in a reducing environment do not pose the environmental or structural risk associated with AASS. Relocating projects to a low-risk

²² See *supra* note 2.

²³ Susan Y. Demas, et al., [*Acid Sulfate Soils in Dredge Materials from Tidal Pocomoke Sound in Somerset County, MD, USA*](#), 42 *Australian Journal of Soil Research* 537, 537–545 (2004); Edward D. Burton, et al., [*Mobility of Arsenic and Selected Metals During Re-Flooding of Iron- and Organic-Rich Acid-Sulfate Soil*](#), 253 *Chemical Geology* 64, 64–73 (2008); Amanda Lindgren, et al., [*Acid Sulfate Soils and Their Impact on Surface Water Quality on the Swedish West Coast*](#), 40 *Journal of Hydrology: Regional Studies* 101019 (2022).

²⁴ Maggie K. Payne & Mark H. Stolt, [*Understanding Sulfide Distribution in Subaqueous Soil Systems in Southern New England, USA*](#), 308 *Geoderma* 207, 207–214 (2017).

²⁵ Nat'l Working Party on Acid Sulfate Soils, *National Strategy for The Management of Coastal Acid Sulfate Soils*, 2000; see *supra* note 7.

²⁶ Eva Högfors-Rönholm, et al., [*Metagenomes and Metatranscriptomes from Boreal Potential and Actual Acid Sulfate*](#), 6 *Soil Materials* (2019).

²⁷ Jesmond Sammut & Rebecca Lines-Kelly, *An Introduction to Acid Sulfate Soils* (1996); Christine C. Nguyen, et al., [*Association Between Heavy Metals and Antibiotic-Resistant Human Pathogens in Environmental Reservoirs: A Review*](#), 13 *Frontiers of Environmental Science & Engineering* 46 (2019).

area and using fill or dredge material that is not from PASS can prevent risks associated with AASS.²⁸

Where AASS have developed through exposure of hypersulfidic materials to an oxidizing environment, remediation techniques can include reflooding or reburial of drained areas to return the soils to an anaerobic state. Care should be taken to avoid drainage of acids and dissolved metals to nearby waterways.²⁹ For recently exposed soils, controlled oxidation of previously anaerobic soils can allow sediments to gradually oxidize so that any acidity formed is neutralized by the soil buffering capacity or filtered out of the system. Another remediation technique is applying and incorporating lime or other amendments, which can neutralize acidity caused by AASS.³⁰

Identification

Sulfide Containing Materials

The Keys to Soil Taxonomy currently recognizes hypersulfidic and hyposulfidic materials (defined below). As mentioned above, going forward the National Cooperative Soil Survey is adopting the term hypersulfidic materials to replace sulfidic materials.

The following definitions are provided in Keys to Soil Taxonomy to classify hypersulfidic materials. They are based on the recommendations of the Acid Sulfate Soil Working Group of the International Union of Soil Sciences³¹ and adapted from current definitions in the World Reference Base for soil resources³² and the Australian Soil Classification system³³.

Hypersulfidic Materials (Formerly Sulfidic Materials)

Hypersulfidic materials are soil materials containing oxidizable sulfur compounds capable of severe acidification as a result of oxidation of contained sulfides. These materials have an initial pH (1:1 water) of more than 3.5. When incubated at room temperature as a layer 1 cm thick under moist aerobic conditions, the pH decreases by 0.5 or more units to a value of 4.0 or less within 16 weeks. More time can be used to let the pH reach a nearly constant value.

Hyposulfidic Materials

Hyposulfidic materials are soil materials containing oxidizable sulfur compounds or sulfide minerals that experience acidification as a result of the oxidation of contained sulfides. These materials become increasingly acidic when oxidized but do not decrease in pH enough to meet the

²⁸ See *supra* note 7.

²⁹ See *id.*; see *supra* note 20.

³⁰ See *supra* note 20; Patrick S. Michael, et al., *The Role of Organic Matter in Ameliorating Acid Sulfate Soils with Sulfuric Horizons*, 255–256 *Geoderma* 42, 42–49 (2015); Arthanur R. Hidayat & Arifin Fahmi, *Impact of Land Reclamation on Acid Sulfate Soil and Its Mitigation*, 20 BIO Web of Conferences (2020).

³¹ L. A. Sullivan, et al., *The Classification of Acid Sulfate Soil Materials: Further Modifications* (2010).

³² Int'l Union of Soil Sciences Working Group, *World Reference Base for Soil Resources. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*, (4th ed., 2022).

³³ See *supra* note 10.

requirements for hypersulfidic soil materials. In addition, these materials have an initial pH (1:1 water) of 4.0 or more, and when incubated at room temperature as a layer 1 cm thick under moist aerobic conditions, the pH decreases by 1 or more units but remains greater than 4.0 after 16 weeks.

Sulfuric Horizon

Sulfuric horizons are a diagnostic for AASS. As described in the Keys to Soil Taxonomy, a sulfuric horizon:

1. Is 15 cm or more thick and composed of either mineral or organic soil material; *and*

Reaction

2. Has a pH value (1:1 by weight in water or in a minimum of water to permit measurement) of 3.5 or less *or* less than 4.0 if sulfide or other S-bearing minerals that produce sulfuric acid upon their oxidation are present; *and*

Evidence of Sulfuric Acid Presence

3. Shows evidence that the low pH value is caused by sulfuric acid. The evidence is *one or more* of the following:
 - a. Concentrations of jarosite, schwertmannite, or other iron and/or aluminum sulfates or hydroxysulfate minerals; *or*
 - b. 0.05 percent or more water-soluble sulfate; *or*
 - c. The layer directly underlying the horizon consists of sulfidic (hypersulfidic) materials (defined above).

Keys to Soil Taxonomy³⁴ includes acid sulfate classes at the great group category as Sulfohemists, Sulfosapristis, Sulfihemists, Sulfisapristis, Sulfiwassistis, Sulfaquents, Sulfiwassents, Sulfaquepts, Sulfudepts, or Sulfaquerts and at the subgroup category as sulfic, sulfuric, or sulfaqueptic. These taxa either contain hypersulfidic materials or have sulfuric horizons within some depth. The Keys to Soil Taxonomy³⁵ identifies soil horizons that contain detectable sulfides with the suffix symbol “se.”

Testing for the Presence of Sulfides

Materials containing sulfides typically have dark colors (e.g., value of 4 or less, chroma of 2 or less) and may experience a drop in pH under moist incubation due to processes other than the oxidation of sulfur compounds—for example, the oxidation and hydrolysis of iron.³⁶ In addition

³⁴ See *id.*

³⁵ See *id.*

³⁶ Abd Rashid Ahmad & Peter Hague Nye, *Coupled Diffusion and Oxidation of Ferrous Iron in Soils. I. Kinetics of Oxygenation of Ferrous Iron in Soil Suspension*, 41 European Journal of Soil Science 395, 395–409 (1990).

to a drop in pH as measured by the oxidized pH or incubation pH method (method 4.3.1.1.1.2),³⁷ the presence of sulfides should be confirmed using one or more of the following field methods for identifying soil materials that meet the definition of hypersulfidic or hyposulfidic materials. Additional laboratory methods that can be used to confirm presence of sulfides are described in the National Acid Sulfate Soils Guidance – National Acid Sulfate Soils Identification and Laboratory Methods Manual.³⁸

*Hydrogen Peroxide Color Change, Presence of Monosulfides (Method 7.1.3.4)*³⁹

In this method, a 3-percent hydrogen peroxide (H₂O₂) solution is applied to soil immediately after the soil is exposed to the air (e.g., freshly broken ped or core interior). With the application of hydrogen peroxide, colors become lighter (i.e., black to gray or brown). A positive reaction, resulting in a color change, indicates the presence of reduced iron monosulfide (FeS), which quickly oxidizes and changes color upon application of hydrogen peroxide. Color change is immediate (within 10 seconds) and discernible upon applying the 3-percent hydrogen peroxide. This method only detects monosulfides and is not applicable for other sulfides (e.g., pyrite, marcasite,).

30-percent Hydrogen Peroxide Effervescence or Color Change (Modified Method 7.1.3.1),⁴⁰ or Both

Reaction with 30-percent hydrogen peroxide is rated by effervescence class.⁴¹ A very slight, slight, strong, or violent effervescence class indicates the presence of pyrite. Wessel and Rabenhorst⁴² note this reaction occurs within 1 to 2 minutes of applying several drops of hydrogen peroxide to the soil material. If enough 30-percent hydrogen peroxide is added to make a slurry, a “runaway” reaction can be produced.⁴³ Unlike the instantaneous reaction of hydrogen peroxide and manganese oxides⁴⁴ or the slow reaction of hydrogen peroxide and organic matter, this reaction begins slowly and builds as the mixture is heated by the exothermic nature of the reaction. The immediate color change response to the addition of hydrogen peroxide can also be noted as an indication of sulfides.

Caution: 30-percent hydrogen peroxide is a very strong oxidizing agent and severely corrosive to skin, eyes, and respiratory tract. Appropriate protective clothing should be worn when handling this agent.

³⁷ See *supra* note 2.

³⁸ Commonwealth of Austl, [National Acid Sulfate Soils Guidance – National Acid Sulfate Soils Identification and Laboratory Methods Manual](#), (2018).

³⁹ See *supra* note 2.

⁴⁰ See *id.*

⁴¹ See *supra* note 3.

⁴² See *supra* note 11.

⁴³ See *id.*

⁴⁴ See *supra* note 3.

Moderate or Strong Sulfurous Odor; Whiff Test⁴⁵

The presence and intensity of a hydrogen sulfide odor immediately after the soil is exposed to air is often an indication of the presence of sulfides. A sulfide odor may result from the volatilization of hydrogen sulfide from the porewater.

Acid Volatile Sulfides (AVS); Modified Whiff Test

A few drops of 10-percent or 1N hydrochloric acid is applied to the soil in a bag, and the bag is closed. The bag is left closed to allow up to several seconds for a reaction. The bag is then opened, and the “whiff test” is applied. A positive reaction for monosulfides is a hydrogen sulfide gas smell.⁴⁶

Caution: Hydrogen sulfide is a toxic gas and care should be taken when applying this test. A broad sweep of the hand to the nose in the open air is sufficient to sense any hydrogen sulfide odor.

Contact

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⁴⁵ See *supra* note 3; see *supra* note 18.

⁴⁶ See *supra* note 11.