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A protocol for digitizing colors: the case of measuring color variables for forested wetland soils

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Abstract A procedure is presented and discussed that highlights the use of the Nix Pro Color Sensor ("Nix") in digitizing soil colors with applications for forested wetland soils. Informed by our soil color investigations using both the Munsell Soil Color Chart (MSCC) and the Nix in forested wetlands of the northern Virginia area, we crafted a standard operating procedure (SOP), adaptable to various locations and/or soil types, that guides users—regardless of knowledge of soil ecology or familiarity with the Nix—to successfully assess and monitor soil colors at various depths. Our SOP outlines steps for digitally collecting, storing, and sharing soil color data. Through the implementation of this procedure, soil color monitoring can enter the digital age, removing barriers of entry to soil color determination and enhancing individuals' interest in monitoring and understanding of the importance of soil color as an environmental and ecological indicator. With continued refinement and adaptation to intended use, the SOP herein presented has the potential to aid wetland/watershed assessment by providing data on soil colors that can be tracked over time while also encouraging public engagement in environmental monitoring of soils.

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Introduction

In the era of global climate change, scientists and managers are faced with various complex ecological problems of which understanding often requires rigorous environmental assessment and monitoring. Nonetheless, a lack of primary data has been a large barrier in effective environmental monitoring given time, costs, and labor that are often required for data collection (Kelly, 2014). Technological advancements have thus prioritized overcoming this barrier through the development of more accessible, easy-to-use, and rapid methods of field data collection. Often in the form of smartphones that can be paired with low-cost sensors, these novel methods have opened up data collection to a larger share of the population outside of trained scientists with applications including environmental outreach and citizen science (Conrad & Hilchey, 2011).

For certain ecosystems in the USA—notably wetlands—their management and protection rests upon the monitoring of key ecosystem properties; thus, they can greatly benefit from expanded spatial and temporal scopes of monitoring. For example, wetland boundary identification (*delineation*) and characterization require monitoring of hydrology, vegetation,

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and soils. Because soil morphology can indicate historic and current long-term conditions of soil saturation, it serves as a useful indicator for year-long wetland monitoring. In particular, s*oil color* is a key, easily observed property linked to wetland biogeochemistry: where soils are naturally colored by organic matter (dark brown-black) and inorganic constituents like iron (red/yellow) and silica (light/white) oxides, fluctuating water tables in wetlands can lead to increased organic matter accumulation, mottled gray-orange horizons where iron has been reduced and reoxidized, and light gray or blueish-green where iron has been reduced and/or leached out of the profile. Color variables thus act as observable indicators of wetland hydrology and its influence in its biogeochemistry (Conrad & Hilchey, 2011; Schmidt & Ahn, 2021a).

Soils are not often the focus of non-professional environmental monitoring endeavors (Palacin-Silva & Porras, 2018; Pocock et al., 2017). The Munsell Soil Color Chart (MSCC), the conventional method for soil color determination, involves subjective judgments by users in determining which of the 440 color chips organized across 13 hue pages best match a soil's color in terms of *hue*, *value*, and *chroma* (Soil Science Division Staff, 2017; X-Rite, 2009). Using the MSCC requires training to overcome perceptual biases, necessitates time for correct color identification and recording, and is often unproductive for the colorblind, who make up 8% of the male population (colorblindguide.com). Furthermore, perceived colors of MSCC chips are influenced by chart aging and field conditions (Turk and Young, 2020). While various lab-based alternatives to the MSCC have provided solutions to these problems—e.g., measuring colors objectively via hardware-software complexes like spectrophotometers (Torrent & Barrón, 1993; Ukrainskiy et al., 2021), and using quantitative and continuous color variables like the Commission on International Illumination (CIE) L*a*b* system for color characterizations (Vodyanitskii & Kirillova, 2016)—they nevertheless fail to provide a method that can be accessibly deployed in field data collection.

Digitizing field-based soil color methods can be a key aspect of moving soil monitoring into twenty-first century data science as it can provide the dual benefit of eliciting greater representation of the average observer in environmental monitoring activities of soils (Hirmas et al., 2016). Relatively few studies have used alternatives beyond the MSCC to measure soil color (Schmidt & Ahn, 2019), but a promising digital tool, the Nix Color Sensor (Nix), has risen to the forefront of several investigations since 2016 (Schmidt & Ahn, 2021a, b; Stiglitz et al., 2016a, b, 2017; Mukhopadhyay and Chakraborty, 2020; Swetha and Chakraborty, 2021). Capable of being used by professionals and laypeople alike, the relatively inexpensive (~$350), diamond-shaped colorimeter scans surfaces with its ~ 2 cm^2 aperture and instantaneously sends color measurements—in the form of 15 color variables from 5 color spaces—to a Bluetooth-linked smartphone or tablet. Our field-based soil color investigations within forested wetlands of the northern Virginia region highlight the utility of the Nix to not only relate to Munsell value and chroma (Schmidt & Ahn, 2021b) but also signal SOC contents (Schmidt & Ahn, 2021a). Given its portability, ease of use, and digitized measurements, the Nix offers a promising avenue of quicker, more objective color determination for SOC estimation, wetland color identification, or other versatile color monitoring applications for the average citizen.

We herein share our standard operating procedure (SOP) applicable to any user with a smartphone and Nix sensor for observing, measuring, and digitizing soil colors. By sharing this procedure, we hope to promote data science of soil environmental monitoring so that professionals, watershed managers, students, and the general public alike can participate in monitoring/assessing the soils beneath their feet.

Deployment of the procedure—soil color measurements

Soil color measurement can be achieved following our SOP; required materials include a smartphone, Nix sensor, soil probe, trowel, ruler, and butter knife. The two-page SOP was created with the intent for users to measure (i.e., *scan*) colors using a 30-cm soil probe (minimum 2.54 cm diameter) to fit the width of the Nix aperture and edges at 3 depths—soil surface, top 0–15 cm, and 15–30 cm. The SOP is flexible and can be modified in many ways, including using a trowel for excavation instead of sampling with a soil probe, or simplifying the procedure to record surface color only, such that no soil disturbance is required. Through the procedure, untrained users are guided through (1) Nix best practices, (2) navigating and using the Nix app on their smartphones, (3) soil sampling, (4) measuring soil colors at multiple depths, and (5) exporting,

Table 1 General procedure from the standard operating procedure (SOP) that students were to follow; necessary materials included a smartphone with the Nix Pro Color Sensor app and camera, the Nix, and a trowel, soil probe, butter knife, and spray bottle

Before sampling	• Download Nix Pro Color Sensor App
	• Turn on picture geotagging
	• Make sure Nix is charged and paired to phone/tablet
At Sampling plot	• Have trowel, soil probe, water (spray bottle), Nix, and Bluetooth-linked phone/tablet on hand
	• Clear litter from soil surface at desired location
	• Take geotagged pictures of plot and surrounding area
Soil surface color	• Use trowel to clear soil surface of any woody debris/leaves and ensure a smooth soil surface
	• Place the Nix on top of the cleared soil surface with subtle pressure on top to ensure aperture edges are in contact with soil
	• In Nix app, press "Scan"; save color scan in desired folder named to a standard convention "SitePlot_0cm"
0–15 cm and 15–30 cm color preparation	• Using a ~ 30 cm soil probe, push the probe into the soil; once it is all the way inserted, pull the probe out
	• Create a longitudinal "cross-section" surface by cutting down the length of the core using a knife held parallel to the probe
0–15 cm colors	• Within the top half of the probe, find a homogenously colored area under the very dark upper layer; this will be the scan location
	• At the chosen measurement location, smooth/flatten the cross-section surface by gently pressing down without blending colors
	• Place the Nix on top of the chosen location with subtle pressure on top to ensure aperture edges are in contact with soil/probe
	• In Nix app, press "Scan"; save color scan in desired folder named to a standard convention "SitePlot_0to15cm"
15–30 cm colors	• In the bottom half of the probe, find a homogenously colored area under the very dark upper layer; this will be the scan location
	• At the chosen measurement location, smooth/flatten the cross-section surface by gently pressing down without blending colors
	• Place the Nix on top of the chosen location with subtle pressure on top to ensure aperture edges are in contact with soil/probe
	• In Nix app, press "Scan"; save color scan in desired folder named to a standard convention "SitePlot_15to30cm"
Tips for all measurements	• Make sure to moisten site of soil color measurement with spray bottle until it is moist enough that it does not change color
	• Place the Nix on top of the cleared soil surface with subtle pressure on top to ensure aperture edges are in contact with soil
	• Do your best to avoid very mottled areas, but if color uniformity cannot be guaranteed, simply find a representative area to scan
After sampling	• From each site, all scans will be saved in the Nix app within the folder ("swatch") name given to them
	• Export them in the app by navigating to Menu → Settings → Export Scanned Colors; find the folder (swatch) with your saved scans
	• The resulting.csv file will have the color name in column A, time stamp in column C, and color variables in columns D through AB. Geotagged information (latitude, longitude) can be matched to color names manually on a scan-by-scan basis

downloading, and sharing data. A summary of the procedure is outlined in Table 1.

Nix color sensor familiarization

While use of the Nix to measure soil color may not require training to overcome personal biases, it is enhanced through some familiarity of how it works, what data it stores for the user, and what quality control issues to avoid. Detailed in Schmidt and Ahn (2021b), a scan may only be completed after the user has downloaded the Nix Pro app on their Android or Apple device and connected the Nix to their device via Bluetooth. When a scan is conducted, the Nix has a pre-calibrated light source that shines light onto whatever surface it is placed on. Data is wirelessly sent to the app, which then visually displays the measured color on the screen with reports of several color spaces and variables like RGB *R*, *G*, and *B* (see Schmidt and Ahn, 2021b). The user must *save* color scans and provide an appropriate name to store and access all 15 color variables from the 5 color spaces recorded with each scan, including CIE–L*a*b*, L*C*h, and XYZ color spaces; RGB; and CMYK. To access a color scan's values for all 15 variables, the user must first export scanned data to a file stored as comma-separated values (.csv), which can subsequently be opened on their device or an accompanying computer.

Measuring location of scans

Currently, the Nix app does not geotag scans; for geospatial environmental monitoring applications, it is thus necessary to record location separately. Our procedure encourages users to turn on their smartphone's geotagging feature to record location within site and/or soil probe pictures; alternatives such as a dedicated GPS device like a GPS watch are also avenues for collecting location data. Such latitude and longitude data must be added to soil color monitoring data after exportation from the Nix app.

Best practices for all color measurements

Overall techniques to obtain accurate color measurements with each scan are included to minimize error from user subjectivity and Nix technical functioning.

1. To ensure the Nix shines light onto the sample area alone, edges of the Nix aperture must be firmly in contact with the soil surface in question by applying slight pressure to the top of the Nix when conducting a scan.
2. As the Nix provides one color measurement independent of the color heterogeneity of the surface it is scanning, some subjective judgment in color scans can ensure accurate data through the avoidance of areas that show mottled color patterns. While this may be challenging with wetland soils that have many small-sized concentrations and depletions, we highly recommend that as much care as is feasible is taken to place the Nix on top of a homogenously colored area. Where it is not feasible to ensure a homogenously colored area fits within the aperture, it is recommended to observe in situ colors rather than smudging them.
3. Surface heterogeneity must be avoided to ensure color accuracy and reproducibility: where cracks or areas of surface roughness are encountered, we recommend using a cloth-covered hand to apply downward pressure on the soil surface, delicately pressing down the surface to form a smooth, even surface.
4. Similar to the procedure required when using the MSCC, if too much water is present, soil moisture should be relatively controlled through draining and/or absorbing water off of the soil surface to be scanned (Stiglitz et al., 2016b). Disposable paper wipes (e.g., Kimwipes) or soft paper tissue (e.g., Kleenex) can be used to gently absorb water off of the soil surface whose color to be scanned. One should not rub the wipes/tissues on the soil surface, but should simply place them on the surface to absorb any surface water while minimizing any disturbance to the soil surface for Nix scanning.
5. The aperture of the Nix should always face down to minimize dust settling on the light source. To ensure soil does not dirty the aperture area, the Nix's aperture edges can be gently dabbed with a Kimwipe or Kleenex as needed.

Measuring soil colors for three different depths

Necessary for any soil investigation, the first step of monitoring requires the removal of unconsolidated surface debris before measuring colors using a trowel or one's own hands. The user should look for a smooth area of soil with little or no surface heterogeneity and place the Nix on top of the ground with slight pressure before scanning (Fig. 1). Scans can be saved following a standardized nomenclature that accounts for site name/location, potential for sample replicates, and depth of scan, each separated by a delimiter like an underscore.

At the same location as the ground surface scan, the soil probe is used for belowground color measurements. After yielding a ~ 30-cm core using a probe, colors within the core are exposed by creating a cross-section surface by carefully sliding a knife along the probe and longitudinally cutting the core. Though initially containing cracks, bumps, or protruding roots, procurement of a smooth and flat core cross-section is achieved by delicately pressing into its surface.

Cross-section cores are directed to be scanned twice: once for the top layer of the core (above 15 cm) and once for the bottom layer of the core (bottom portion of the core; 15–30 cm). While the core's color continuum will depend on soil horizonation, the procedure assures that two depth increments will be recorded.

Exporting, exploring, and assessing scanned colors

Each saved Nix scan can be accessed and exported to a comma-separated values (.csv) file within the Nix app (Table 1). A.csv file can be opened in a software like Microsoft Excel to view, sort, explore, and assess exported color scans using any of the 15 color variables; GPS coordinates can be added to each scan (i.e., row) where applicable. Via Excel, users can compare color variables between sites or depths and/or visualize ranges of different Nix variables (Schmidt & Ahn, 2019). When comparing colors for scans from starkly different settings or depths, one may also focus on some of the notable Nix color variables that relate to Munsell value, chroma, and SOC, respectively (see Schmidt & Ahn, 2021a, b)—e.g., comparing CIE L^* (lightness) and C^* (chroma) between iron-depleted wetland soils and iron-rich soils of well-drained forested upland soils.

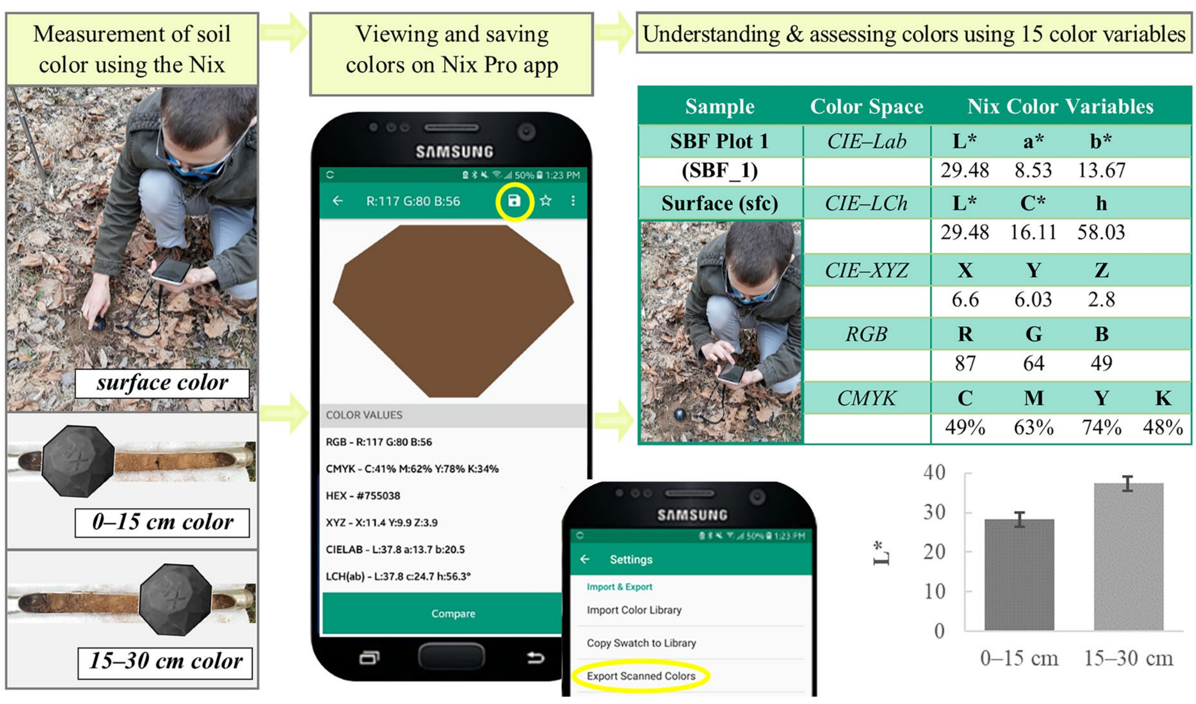

Fig. 1 Summary of the key aspects of the standard operating procedure (SOP) to measure soil colors using the Nix, including assessment and comparison of measured color variables like the Commission on International Illumination (CIE)–$L^*a^*b^*$ L^* variable

Environmental soil literacy: linking color to soil science through digital data

While the Nix automates the process of color determination that is more deliberate and tangible when using the MSCC, it can nonetheless yield a similar sense of appreciation for and interaction with soils. Due to its digital integration with devices, the Nix can be employed for college soil classes as most students carry their smartphones. Observations taken down on pen and paper may be the activity of a traditional scientist, but smartphone-based societies have made the creation of digital content a ubiquitous, almost craveable action that renders a sense of digital achievement to the data collector that desires to "achieve" more (Holmgren, 2020). Furthermore, the digital nature of the data records removes challenges associated with maintaining record integrity in bad weather, data storage, and data aggregation.

Even without a crowdsourced component to the Nix color sensor and app, the Nix provides ample opportunity for management-based monitoring of local, regional, and/or global soil colors that can dually enhance community environmental literacy. The stated accessibility of the in-field measurement with the Nix may allow scientist-led trainings and/or monitoring events for citizen scientists and soil educators beyond the digital divide that may encourage inequality of devices by economic, racial, political, and geographic discrepancies (Andrachuk et al., 2019).

Furthermore, color measurements from the Nix can act as indicators of either well established or novel hydrologic regimes; for the latter, soil biogeochemical processes can lead to hydric gray/gley colors in as little as 21 days (He et al., 2003), and monitoring of soil color using the Nix can document "accidental" wetlands often observed in areas that become flood-prone after altered weather patterns, landcover, and/or stormwater management lead to increased urban flood frequencies and intensities (Palta et al., 2017).

Considerations for further study

Proper and standardized techniques using the Nix presented here can transform objective measurements of soil colors into informative ecosystem and/or land characterizations for any type of observer. Further study should focus on standardizing the act of soil color measurements at a specific location. The significance of soil colors is inherently tied to color depth and thickness; ideally, both must be standardized, controlled, and/or noted in monitoring data. When assessing soil colors for presence of hydric soils per the USDA field indicators, the presence of a depleted soil matrix at 15 cm provides a different implication from its presence at 35 cm, and a depleted soil matrix at 15 cm with a 1-cm versus 15-cm thickness holds different implications (USDA–NRCS, 2018). An alternative, simplified approach could be to focus exclusively on color of the soil surface as it worked well in this study. Thus, future research could focus on the relationship between surface colors and functional attributes of soil ecology to provide a universally applicable and easy-to-monitor indicator of soil function. For instance, a recent work successfully used surface colors of soil to indicate erosion rates (Thaler et al., 2021).

Our experiences suggest that the Nix can accurately assess matrix colors of mineral wetland soils at different depths where redoximorphic features are in low frequency; however, the Nix cannot accurately measure colors where dominant soil colors do not easily fit within the Nix's 1.5-cm aperture. For wetland soils, the Nix is thus most appropriate for investigating wetlands with thick O horizons or gleyed or depleted horizons that begin above 30 cm.

The SOP has clear potential for environmental education: the procedure allows users to (1) collect and monitor soils fairly quickly, (2) produce numerical and digital data, and (3) compare colors across sites and/or depth intervals. To properly advocate for the use of the Nix in a greater community and/or global setting, an interface that instantly appends Nix measurement data with GPS data—be it privately or to a crowdsourced medium—is necessary and feasible. Such development could allow for mapping of colors across an area, highlighting areas requiring greater monitoring investment and areas that exhibit signs of wetland development.

Conclusions

The study presents a SOP that can be used to record soil colors for environmental monitoring in the digital age. The SOP provides a step-by-step outline for collecting, storing, and sharing soil color data that contrasts using the MSCC. Using Nix sensor with the SOP can make soil color determination easier and more accessible to those who are interested in soil color monitoring to understand the significance of color as an environmental and ecological indicator. Through the dissemination of this procedure, we are optimistic that the Nix can benefit scientists, land managers, teachers/students, and community members alike to enhance environmental monitoring of soil while connecting individuals to their otherwise unseen soilscape. Some modifications including software development may allow Nix measurements to be connected to location and soil biogeochemistry in a more instantaneous and crowdsourced setting while also providing improved structure over measurement settings. We encourage interested researchers to connect with us for future methodological refinement and collaboration.

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Author contribution Stephanie Schmidt: data collection (field work), data analysis, writing – original draft preparation and revision.

Changwoo Ahn: conceptualization, supervision, data analysis, writing – reviewing and revision.

Availability of data and material Raw data will be provided if asked for.

Declarations

Competing interests The authors declare no competing interests.

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