



# Response of wetland soil carbon to groundwater conservation: Probabilistic outcomes from error propagation



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## ABSTRACT

Water loss compromises functions performed by wetland ecosystems. Efforts to rehabilitate wetland function typically begin with attempts to reestablish hydrology. These activities are often not monitored, so tools to extract information from them could partly offset the lost opportunity to learn from whole-ecosystem hydrological manipulation. In 2002, groundwater abstraction was lessened by 35% throughout 1700 km<sup>2</sup> of west-central Florida (USA). I assembled a pathway of correlations to project how this hydrological manipulation affected water levels and soil carbon (C) storage in overlying wetlands. Parameter values and residual error in these statistical models were resampled from known variances, thereby propagating uncertainty through the pathway of relationships, and expressing the response of soil C probabilistically. Projected soil C probability distributions were most distinguishable between full and moderate (30% less) abstraction. With more severe abstraction cutbacks, gains in projected soil C became more marginal and uncertain, suggesting that wetland soil C pools are not notably impacted by low-volume groundwater abstraction. Reducing uncertainty in projected soil C will require better understanding the dynamic response of soil C to increases in the amount of time that wetland soil is inundated. The step-by-step error propagation routine presented here is a platform for assimilating information from diverse sources in order to project probabilistic responses of ecosystem function to wetland restoration attempts, and it helps identify where further certainty is most wanted in a pathway of cause–effect relationships.

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## 1. Introduction

Wetland structure and function are defined by wetland water balance, meaning that water loss poses a threat to wetland conservation (NRC, 1995). Wetland water loss occurs for several reasons, including climate change (Klein et al., 2005; Roulet et al., 1992), land reclamation (Baldock et al., 1984; McCorvie and Lant, 1993), and water appropriation (Rains et al., 2013). Water appropriation is a growing concern because groundwater abstraction is now faster than aquifer recharge (Gleeson et al., 2012; Richey et al., 2015), which dictates falling water tables. This syndrome of wetland dewatering presents the restoration question of whether reestablishing wetland hydrologic regimes will rehabilitate wetland ecosystem structure and function (Acreman et al., 2007; Zedler, 2000).

One prominent function of wetland ecosystems is the storage of carbon (C) in soil organic matter (Ahn et al., 2009; Marín-Muñiz

et al., 2014). Wetlands store 9–19% of the C contained in the terrestrial plus surface-ocean biosphere, mostly in their soils, yet cover  $\leq 1\%$  of the planet surface (Bridgham et al., 2006; Mitra et al., 2005). Such massive C storage supports several ecosystem services: it mitigates global climate by sequestering carbon away from the atmosphere, it supports secondary productivity by supplying abundant energy for heterotrophic organisms, it benefits water quality by fueling the removal of pollutants from hydrologic flowpaths, and it supports primary production by releasing a steady supply of plant nutrients bound to soil organic C (SOC).

These SOC-mediated services are vulnerable to water loss because the preservation of wetland soil C depends on frequent soil saturation. Soil organic C accumulates in wetlands because soil enzyme activity and decomposition are slowed by prolonged soil saturation and anoxia (Day and Magonigal, 1993; Freeman et al., 2004; Lewis et al., 2014; McLatchey and Reddy, 1998; Skopp et al., 1990). Conversely, water loss triggers C export from wetlands by stimulating the oxidation of organic matter (Bridgham et al., 1998; Fenner and Freeman, 2011; Updegraff et al., 1995) and by inducing export of dissolved organic matter in outflowing water (Pastor et al., 2003; Strack et al., 2008). By accelerating organic matter efflux

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from wetlands, dewatering shrinks the standing stock of C in wetland soils (Bridgham et al., 2008; Craft and Richardson, 1993; Lewis and Feit, 2015; Pitkänen et al., 2013).

A pressing question is therefore whether wetland SOC stocks can be recovered by reestablishing high water tables. Indeed, several studies (mostly in peatlands) generally find that rewetting dewatered wetlands can cause C exports to slow within months of implementing restoration measures, and cause wetlands to become net C importers within months to years (Cagaman and Waddington, 2008a,b; Tuittila et al., 1999; Waddington and Price, 2000). Soil C stocks in rewetted wetlands can reach levels found in intact reference systems within a decade (Gao et al., 2014), although a meta-analysis of diverse wetland types reveals that carbon stocks in restored wetlands reach only 50% of natural levels even 20 years after restoration efforts (Moreno-Mateos et al., 2012). In situ studies such as these, where hydrology is manipulated at the whole-wetland extent, are valuable, yet they are unfortunately expensive and rare. In many instances of hydrological manipulation, adequate data are not collected to determine if ecosystem services have recovered in turn. The failure to monitor ecosystem response to attempted restoration is a missed opportunity to learn from the widespread management practice of whole-system manipulation, and it diminishes return on investment in these expensive activities (Alexander and Allan, 2006; Bernhardt et al., 2005). Accordingly, methods to extract information from unmonitored restoration activity could return some of this lost value (Berkowitz, 2013).

One such method is to aggregate information that links hydrological manipulation with ecological responses such as soil C storage. For instance, it may be feasible to combine information from multiple studies to assemble a step-by-step pathway of relationships ( $X_1 \rightarrow \dots \rightarrow X_n \rightarrow Y$ ) that connects the mechanism of wetland water loss (e.g., groundwater abstraction) with water table elevation, wetland inundation time, and ultimately wetland soil C storage. This approach, known as step-by-step prediction, sequentially links multiple empirical models such that the predictor ( $X_n$ ) of one variable ( $Y$ ) is itself predicted by at least one other ( $X_{n-1}$ ) (Håkanson and Peters, 1995). This approach is illustrated in a step-by-step model that predicts mercury (Hg) concentrations in piscivorous game fish ( $Hg_{pi}$ ) in boreal cool-summer lakes. In this illustration, Håkanson (1999) identifies an empirical regression model of  $Hg_{pi}$  as a function of Hg concentrations in planktivorous prey fish ( $Hg_{pe}$ ), a model of  $Hg_{pe}$  as a function of several variables including bioavailable reactive Hg concentrations in water (RHg), and a model of RHg as a function of lake color and tributary discharge. A step-by-step model is then assembled to predict  $Hg_{pi}$  from lake color and discharge. This approach is used in place of a sole multiple regression model that might predict  $Y$  from all  $X_1 - X_n$  in cases where causal relations truly are sequential and in cases where each empirical relationship is fit using a different dataset. Error is introduced at every step, inflating confidence limits around the final predicted variable,  $Y$  (Håkanson, 1999).

An analogous sequence of relationships could inform how wetland soil C storage might respond to lessened groundwater abstraction. However, uncertainty would accumulate across such a sequence of relationships. Consequently, some projected outcome (soil C storage) has a probability distribution, rather than a discrete value, given a manipulation such as lessened groundwater abstraction (Carpenter, 1998). The important question is whether projected increases in soil C are sufficiently large, relative to uncertainty, for probabilities to be distinguished between dewatered vs. hydrologically restored wetlands.

Soil C (or any predicted response variable) can be expressed probabilistically by incorporating parameter uncertainty in models that relate it to its predictor variables, or by adding residual error ( $\varepsilon$ ) to model output ( $\hat{Y}$ ). Uncertainty in parameter estimates can

be incorporated by resampling from known parameter variances, so parameter values are different every time a model projects a response variable (Crowley, 1992). Likewise, the  $\varepsilon$  added to  $\hat{Y}$  can be resampled from a known distribution of residuals. Using a resampling approach in each relationship will propagate error through a step-by-step pathway. For example, Blukacz et al. (2005) compute annual lake zooplankton production from directly measured variables through several intermediate calculations. They incorporate statistical error at each step by resampling from raw data or from probability distributions, thereby better estimating the full magnitude of error in their final computed variable (zooplankton production). Treating ecological outcomes as probabilistic takes advantage of pre-existing information, such as quantified parameter variance (Holtgrieve et al., 2010). It also avoids the unrealistic expectations conveyed by discrete model predictions, which in turn may result in more easily defended decisions about implementing management strategies (Olson et al., 1998).

Here, I propagate statistical error through relationships linking groundwater abstraction, wetland hydrology, and soil C storage in order to project a probability distribution for wetland soil C when groundwater abstraction is lessened. This procedure is applied to west-central Florida (USA), where wetlands sit over a groundwater aquifer that is abstracted to serve the Tampa Bay region. In late 2002, groundwater abstraction volume was lessened in order to mitigate harm to surface waters (TBW, 2009). My objectives here are to propagate error through statistical relationships that link groundwater abstraction to soil C in order [1] to determine whether soil C probability distributions can be distinguished between scenarios with restoration (lessened groundwater abstraction) and without restoration (historically intense groundwater abstraction), and [2] to identify where to reduce error in order to best tighten these soil C probability distributions. An additional objective was [3] to corroborate whether wetland hydrology actually was rehabilitated when groundwater abstraction was lessened.

## 2. Methods

### 2.1. Study region

Freshwater mineral-soil wetlands cover about 14% of west-central peninsular Florida, and commonly form in depressional basins. Most basins are cypress forest swamps characterized by pond cypress (*Taxodium ascendens*, sometimes considered a variety of *Taxodium distichum*) (Haag and Lee, 2010). They are colloquially referred to as cypress domes, as the tallest trees are found in the basin center, creating a dome-shaped canopy. These basins are fed by an unconfined surficial aquifer and are seasonally inundated even in a hydrologically unimpaired state. These wetlands are interspersed throughout an upland landscape of pine flatwoods habitat, which is composed of *Pinus* species and the shrub saw palmetto (*Serenoa repens*). This low-elevation (15 m) coastal region along the Gulf of Mexico has little topographic relief and receives 1353 mm/yr of precipitation. Average temperatures are 15°C in January and 28°C in August, with a mean humidity of 73% (National Climatic Data Center, 1981–2010).

This wetland complex overlaps the 1700-km<sup>2</sup> Northern Tampa Bay water management zone (Rochow, 1998). Within this management zone, groundwater from the confined Floridan Aquifer (which lies beneath a clay confining layer and the unconfined surficial aquifer) is abstracted to meet the demands of 2.87 million people in the Tampa Bay metropolitan area, and associated agricultural and extractive industries. In 2012, water was abstracted from the Floridan Aquifer at 681 ML d<sup>-1</sup> and delivered to urban (76%) and agricultural (24%) users (Ferguson, 2014). Of this volume, 298 ML d<sup>-1</sup> was taken from a consolidated network of 13

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