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RESEARCH ARTICLE

# Restoring the foundation of the Everglades ecosystem: assessment of edaphic responses to hydrologic restoration scenarios

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**Because of the significant role soils play in the health and function of the Everglades ecosystem, soil conservation is a central tenet of Everglades restoration. As such, it is critical to anticipate ecosystem responses to hydrologic restoration activities from the perspective of the soil component. The broad goal of this work was to investigate the resulting effects of various hydrologic restoration scenarios on soil processes of phosphorus and carbon accretion by modeling soil edaphic processes using the Everglades Landscape Model. The results of modeling effort suggest that full implementation of the Comprehensive Everglades Restoration Plan provides the greatest spatial reduction of phosphorus (P) enrichment throughout the system. The existing condition baseline (ECB) scenario, which represents the current hydrologic and nutrient impaired condition, produced the highest observed rates of soil carbon accretion; however, this scenario is successful in accretion of soil carbon due to elevated P conditions, not restored hydrology. Management implications of restoration with respect to soil elucidated from this work include: (1) prioritization of habitat quality and ecosystem function (via P reduction) over carbon sequestration potential and (2) need to reduce P inputs before restoring hydrologic connectivity and historic flows.**

**Key words: carbon, decompartmentalization, Everglades, hydrology, phosphorus, restoration, soil accretion**

## Implications for Practice

- Although full ecosystem restoration is often a goal, iterative evaluation of partial restoration scenarios is valuable to support the final decision for full or partial restoration. Communication of these findings by scientists and engineers to decision makers is critical to any successful restoration effort.
- Resource managers may be forced to assess trade-offs between ecosystem services (such as carbon storage) and ecosystem quality (i.e. habitat) during the restoration process. Well-articulated restoration goals allow for prioritizing of these trade-offs.
- Understanding the effects of various restoration activities on soil resources is necessary in overall decision making process for wetland restoration efforts, especially when nutrients or contaminants are of considerable concern.

## Introduction

Although a foundational ecosystem component, soil is often less recognized or underappreciated due, in part, to the subtle nature of change associated with subsurface biogeochemical processes. Changes to wetland soil characteristics, whether in nutrient content, metals, organic contaminants, or simple changes in physical properties, are not readily apparent. Rather, other ecosystem components, such as vegetation or water chemistry, that can be modulated by soil quality are often the first indicators of ecosystem changes in soils (Reddy et al. 2011). The ecological significance of soils is exemplified in the Florida Everglades, where it serves as both the foundation of the ecosystem and largest storage pool of ecologically relevant elements (Craft & Richardson 1993; Reddy et al. 1993; Osborne et al. 2015).

Organic soil formation requires anaerobic conditions brought about by long hydroperiods and it is composed predominantly of organic remains of dead plants. Histosols (soils consisting of predominately organic matter) dominate the Everglades with Everglades and Loxahatchee series soils encompassing over 7,000 $\mathrm{km}^2$. Everglades series underlies much of the central and southern Everglades and Loxahatchee series soils occur in deeper marsh areas underlying Loxahatchee National Wildlife Refuge, the northeastern areas of WCA-2A, and the Shark River Slough (Gleason & Stone 1994). Everglades organic soil is formed mostly from partial decomposition of sawgrass (*Cladium jamaicense* Crantz), the dominant wetland plant species, whereas Loxahatchee organic soil forms from vegetation of

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sloughs, especially water lily (*Nymphaea odorata*). Organic soil thickness ranges from approximately 3.0 m in Loxahatchee NWR and decreases to a minimum of 0.2 m in the Everglades National Park (Reddy et al. 2005; Scheidt & Kalla 2007; Osborne et al. 2011*b*). Organic soils are subject to subsidence and loss of surface elevation when drained. Compaction and oxidation are considered the primary and secondary subsidence forces respectively, and from a practical standpoint are irreversible (Snyder 2005; Richardson & Huvane 2008; Osborne et al. 2011*b*). It has been proposed that from the 1940s to 1990s the entire Everglades Protection Area lost up to 28% of its soil volume due to soil subsidence (Scheidt et al. 2000).

Soil elevation at the local level is a function of geology, hydrology, and biology. As mentioned previously, local geologic foundations dictate, to a large degree, the hydrology or hydroperiod of a given marsh area. This hydroperiod in turn directly influences the rate of soil accretion, which is dictated by the opposing biological processes of primary production and respiration (Cohen & Spackman 1984). The quality (bioavailability) of organic matter which makes up the soil can also determine rates of accretion as different plant types contribute organic matter of variable quality to the soil (Osborne et al. 2007; Cohen et al. 2011). During the last 1,200 years, the accretion rate of organic soil in the northern Everglades has been found to be approximately 1.6 mm/year (DeAngelis 1994; Gleason & Stone 1994) under inundated conditions. Under aerobic conditions, rapid decomposition can cause soil loss (i.e. negative accretion) of up to 30 mm/year, highlighting the significantly asymmetrical rates of the two competing processes (Stephens & Johnson 1951; Snyder & Davidson 1994; Maltby & Dugan 1994) and the integral role of hydrology in soil dynamics.

Deep organic soils characteristic of much of the Everglades are, by nature, long-term integrators of environmental condition, and as such, serve as a major storage pool for organic matter, macronutrients (N and P), metals (both beneficial and harmful), and anthropogenically derived organic substances (DeBusk et al. 1994; Newman et al. 1997; Bruland et al. 2006; Osborne et al. 2011*a*, 2011*b*). With the advent of drainage within the EAA circa 1900–1910, subsidence of organic soils began. Beginning in 1913, extensive soil subsidence within the EAA was investigated and documented (Davis 1943; Jones 1948; Stephens & Johnson 1951; Gleason & Stone 1994; Snyder & Davidson 1994; Snyder 2005). By draining the waterlogged soils, landscape scale soil oxidation was catalyzed that has resulted in not only great loss of soil (up to 3 m in some areas) in the upper Everglades basin (Everglades Agricultural Area [EAA]), but has also contributed significantly, by way of organic soil mineralization, to elevated phosphorus runoff to the remaining Everglades downstream (water conservation areas [WCAs], ENP)(Snyder 2005; Osborne et al. 2011*b*). Extensive use of agrochemicals and fertilizers has contributed to the increased presence of xenobiotics and nutrients in waters flowing into the Everglades today (SFWMD 2007), requiring the use of extensive stormwater treatment areas or STAs—treatment marshes designed to remove and store nutrients from agricultural waters prior to release into the downstream Everglades (Pietro et al. 2007). Inputs of agricultural runoff carry an assortment of metals, organic chemicals, and nutrients that are detrimental to the system. The most ecologically notable is phosphorus (Davis 1991, 1994; Craft & Richardson 1993; Reddy et al. 1993).

The 1970s through 1990s witnessed significant ecosystem decline seemingly linked to phosphorus enrichment. This resulted in much attention and research concerning P loading to the Everglades WCAs and subsequent ecosystem changes such as vegetative community shifts and habitat degradation that were attributed in the most part to excess soil phosphorus (Davis 1994; Noe et al. 2001; McCormick et al. 2002). Due to overwhelming evidence of P enrichment in the northern Everglades, several studies have been conducted to investigate P enrichment in soils (Koch & Reddy 1992; Amador & Jones 1993; Craft & Richardson 1993; Reddy et al. 1993; DeBusk et al. 1994; Qualls & Richardson 1995; Newman et al. 1997, 1998; Noe et al. 2001, 2003; Daoust & Childers 2004) and in some cases, changes to soil condition over time (Childers et al. 2003; Reddy et al. 2005; Bruland et al. 2006; Rivero et al. 2009). These studies overwhelmingly indicate that inflow waters from agriculture operations upstream have caused P enrichment of soils in many areas across the Everglades landscape (Scheidt & Kalla 2007; Hagerthey et al. 2008; Osborne et al. 2011*b*).

A majority of studies and the scientific community working in the Everglades concur that even small additions of P can have a dramatic effect on ecosystem productivity and functioning (Chiang et al. 2000; Childers et al. 2003; Gaiser et al. 2005). Nowhere are these effects more readily observed than in the changes to periphyton and vegetation. Autochthonous nutrient inputs have resulted in significant alterations to the indigenous system with large expansions of cattail (*Typha domingensis*; Davis 1994; Newman et al. 1998; Craft & Richardson 2008). Cattails are adapted to grow rapidly in the presence of available P, and in doing so, out-compete native vegetation such as sawgrass (*C. jamaicense*; Davis 1991; Davis 1994; Miao & Sklar 1998). Vegetation communities create positive feedbacks to the physical position of soil which in turn influences landscape patterns such as ridges, sloughs, and tree islands (Ewe et al. 2006; Watts et al. 2010; Wetzel et al. 2011), which can be lost due to P induced alteration of these feedbacks processes. Similarly, interactions between water level (natural or managed) and soil elevation (affected by accretion or oxidation) at a given location in the landscape are of great importance in controlling plant community dynamics (Davis et al. 2005; Lodge 2010) and nutrient cycling (Scheidt & Kalla 2007; Osborne et al. 2011*a*).

Because of the significant role soils play in the health and function of the Everglades ecosystem, soil conservation is a critical aspect of restoration (Osborne et al. 2011*b*, 2015). Hence, it is imperative to anticipate ecosystem responses to hydrologic restoration activities from the perspective of the soil component. The goal of the work presented here is to quantitatively compare several hydrologic restoration scenarios on the basis of potential changes to soil phosphorus accumulation and soil carbon sequestration (as soil accretion). The results of this effort provide guidance to resource managers and decision makers with respect to ecosystem level impacts of restoration alternatives to Everglades soil resources.

## Methods

### Restoration Scenarios

As part of an interdisciplinary research initiative, the Synthesis of Everglades Research and Ecosystem Services (SERES) project developed five distinct hydrologic restoration scenarios spanning the existing condition to full implementation of the Comprehensive Everglades Restoration Plan (CERP) approved by the U.S. Congress via the Water Resources Development Act of 2000 (Table 1). Briefly, scenarios chosen for this investigation include: (1) a current condition termed the existing condition baseline (ECB) which reflects current flow and water quality conditions. This option is the "no further action" scenario in which no further restoration activities occur, and assumes recent (2004–2010) historical TP inflow concentrations (that generally exceed 0.01 mg/L). CERP represents full implementation of current restoration plans, with CERP hydrology, and daily dynamic inflow water quality targets of TP averaging approximately 0.01 mg/L (10 ppb), calculated from the results of the DMSTA model (see Naja et al. this issue). All other scenarios also assume those inflow target TP concentrations, calculated from results of the Dynamic Model for Everglades Stormwater Treatment Areas (DMSTA) for each scenario. Each of the below modifications to CERP plans use CERP (not ECB) as the new baseline for relative comparisons, in order to compare the SERES options/scenarios to CERP specifically. Partial CERP (PC) represents scaled back CERP with no water storage reservoir construction. Expanded storage and decompartmentalization (ESD) represents increased water storage capacity in the EAA upstream of the modern day Everglades. ESD also includes removal of several levees that impede flow between WCAs such as WCA3A and WCA3B. The final scenario maximum storage and decompartmentalization (MSD) represents the maximum conveyance of water through the central Everglades. PC, ESD, and MSD are various iterations of water delivery with the caveat that MSD adds significantly more water to the system than PC or ESD scenarios. For a detailed description of the hydrologic scenarios and the process used to define them, please see Wetzel et al. (this issue).

**Table 1.** Water storage, flow, and ecological features of the SERES Everglades restoration scenarios: ASR, aquifer storage and recovery; CERP, Comprehensive Everglades Restoration Plan; ECB, existing condition baseline; ESD, expanded storage and decompartmentalization; MSD, maximum storage and decompartmentalization; PC, partial CERP; WCA, water conservation area. All restoration scenarios leverage CERP target water quality of 10 ppb TP. Table used with permission from Wetzel et al. (this issue). Shaded region indicates existing conditions.

| | *Water Storage* | | *Water Flow* | | | *Ecology* | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Scenario option* | *Lake Okeechobee ASR (acre-feet/yr)* | *Everglades Agricultural Area/Lake Belt Reservoir (acre-feet/yr)* | *Predicted level of historic water flows reaching the Gulf of Mexico (%)* | *Reduction of internal barriers to Flow (%)* | *Additional storm water treatment areas needed (acres)* | *Wading bird flock abundance annual increase (%)* | *Fish density annual increase (%)* | *Overall fire risk (%)* | *Florida Bay Salinity reduction (% closer to target)* |
| *Existing conditions (ECB)* | 0 | 0 | >50 | 125 miles of levees | Current area 60,000 | 90% lost | 0 (multidecadal decline) | Nearly every other year | Too salty |
| CERP | 2,456,000 | 504,000 | 87 | 54 | 33,000 | 10 | 12 | 78 | 50 |
| Modified CERP (PC) | 822,700 | 360,000 | 79 | 54 | 28,500 | 9 | 12 | —67 | 25 |
| Expanded storage (ESD) | 0 | 1,300,000 | 91 | 69 | 47,000 | 8 | 13 | —36 | 50 |
| Maximum storage (MSD) | 0 | 2,700,000 | 90 | 75 | 38,500 | 9 | 15 | —89 | 50 |

### Everglades Landscape Model

Based upon the hydrologic conditions defined by each scenario, flow rates (among other hydrologic criteria) were computed for each water control structure based upon the South Florida Water Management Model (SFWMM), which is also known as the $2 \times 2$ model because the unit of area for this model is a $2mi \times 2mi$ grid across the system. The hydrologic parameter output of the $2 \times 2$ model provided the input for the Everglades Landscape Model (ELM V2.8.4) (Fitz et al. 1996, 2004, 2011), the chosen modeling tool for assessing soil conditions in the Everglades for this assessment. ELM has 40 times finer resolution than the SFWMM, as the model grid is composed of 500 m × 500 m square cells. This model has been well tested and validated on several other projects, including the WCA 3 Decompartmentalization and Sheet Flow Enhancement Project (Decomp) (SFWMD 2016) and remains the best model for prediction of landscape level changes in soil nutrients (soil TP, P accumulation rate) and carbon sequestration rates (soil accretion).

General assumptions of the ELM include utilization of 1965–2000 climate data to generate environmental conditions for runs and 1980–2014 observed flow and nutrient concentrations for flow models and nutrient dynamics. Model run starts at time zero (2015) and runs for 36 years (through 2051) which we refer to here as the period of simulation (POS). Although future climate changes are anticipated to have significant effects on soil resources during this time period (Orem et al. 2015), these and sea level rise were not considered for the SERES project.

Model results were provided on basis of changes to unit area (hectares) of the landscape within the total Greater Everglades Ecosystem extent which consists of 1,039,400 ha for the ELM domain. Comparisons were based upon spatial extent of change from each restoration option prediction, and included calculation of mass differences in soil TP and C sequestration from the model output.

To calculate mass differences of soil TP and C sequestration, mean soil bulk density (BD), initial TP concentrations, and initial soil total carbon (TC) were derived from the 2003 ESM dataset ($n = 650$) (Reddy et al. 2005; Osborne et al. 2011*b*). The data utilized to determine the mean values for these variables were from soils sampled in the WCAs and included WCA-1, 2A, 2B, 3A, and 3B. Model output was expressed in spatial coverage of soil accretion rates, with delineations at the two criteria of greater than or equal to 0.25 and 2.0 mm/year. For the purposes of this work, we consider the C sequestration potential to be relative differences among the options, and absolute magnitudes may be underestimates of true C sequestration. For soil TP, the delineation criteria were set at 400 and 500 mg P kg$^{-1}$ soil to reflect both the CERP restoration goals (400 and 500 mg P kg$^{-1}$ soil) and the definition of P impacted soils (500 mg P kg$^{-1}$ soil) used by the State of Florida for assessment (SFWMD 2016). As with soil accretion, the differences between the restoration options considered the differences in total area P accretion within the Greater Everglades domain.

Calculations of soil C sequestration were computed as follows:

$$\text{Total area (ha)} \times 10{,}000\,\text{m}^2$$
$$/\text{ha} \times \text{accretion rate (0.00025 m)} = \text{soil volume } \left(\text{m}^3\right)$$

then,

$$\text{Soil volume } \left(\text{m}^3\right) \times \text{mean bulk density } \left(\text{kg/m}^3\right)$$
$$\times \text{ mean total carbon (kg/kg)} = \text{total mass C (kg)}$$

for total tons of C sequestered over the POS

$$\text{Total tons for all rates} \times \text{POS (36 years)}$$
$$= \text{total C sequestration (metric tons)}$$

## Results

### Soil Accretion

Summary of the soil accretion results of ELM model runs (Table 2) indicate that ECB exhibits the highest C sequestration potential with respect to the options evaluated here. The ECB conditions result in 846,675 ha of the landscape having a soil accretion rate of 0.25 mm or more per year and 116,225 ha equal to or greater than 2 mm/year. Comparatively, the CERP results suggest that 845,440 ha would have 0.25 mm or more and 95,900 ha would be greater than or equal to 2 mm/year. PC showed the next highest sequestration potential with 840,775 and 94,425 ha with rates of 0.25 and 2.0 mm/year, respectively. ESD was lower with 833,000 ha with rates greater than or equal to 0.25 mm/year and 82,400 ha with rates above 2.0 mm/year. MSD had the lowest sequestration potential with 828,725 ha greater than 0.2 mm/year and only 69,000 ha with rates greater than 2.0 mm/year.

The total estimated C sequestration was highest for ECB with 4,132,700,000 metric tons over the 36-year POS. CERP and PC were similar with 3,854,500,000 and 3,869,700,000 tons, respectively. ESD resulted in 3,710,000,000 tons of carbon sequestered in accreted soils while MSD resulted in the lowest C sequestration, with 3,555,400,000 tons totaled over the POS.

In comparison to CERP, ECB showed higher soil accretion rates in WCA-2A, NW WCA-3A, and ENP (Fig, 1A). PC showed lower organic soil accretion in the northern WCAs than CERP scenario and slightly greater soil accretion rates in WCA-3B (Fig. 1B). Greater differences were observed between CERP and the latter options. CERP has substantially higher accretion rates in the WCAs as opposed to ESD and MSD (Fig. 1C & 1D); however, these alternatives did show higher rates of soil accretion in the SE and SW portions of Shark Slough in ENP.

### Soil Total Phosphorus

Model runs suggest that spatial coverage of soils in excess of 400 mg/kg TP is only 4,925 ha greater under ECB than CERP (Table 3). However, CERP is significantly lower with 17,725 ha of soil (209,125 ha ECB vs. 189,800 ha CERP) in spatial impact with respect to the 500 mg/kg threshold of soil TP. In contrast to ECB, PC has 5,525 ha and 2,950 ha more area exceeding the 400 and 500 mg/kg P threshold, respectively, resulting in better performance than ECB. ESD showed worse performance with respect to soil TP with 502,875 ha above 400 mg/kg P (10,200 ha > CERP) and 211,350 ha above 500 mg/kg soil P (19,950 ha > CERP). MSD had the poorest performance of all options with 503,050 ha exceeding 400 mg/kg and 225,825 ha exceeding 500 mg/kg soil TP. This results in 10,375 and 34,425 ha greater area compared to CERP with 400 and 500 mg/kg soil TP, respectively.

ELM output for soil TP levels under the different scenarios (Fig. 2) indicates that ECB results in significantly higher soil TP in WCA-1, 2A, 2B, northern and central portions of 3A and the Holeyland/Rotenberger tracts. There are also areas in

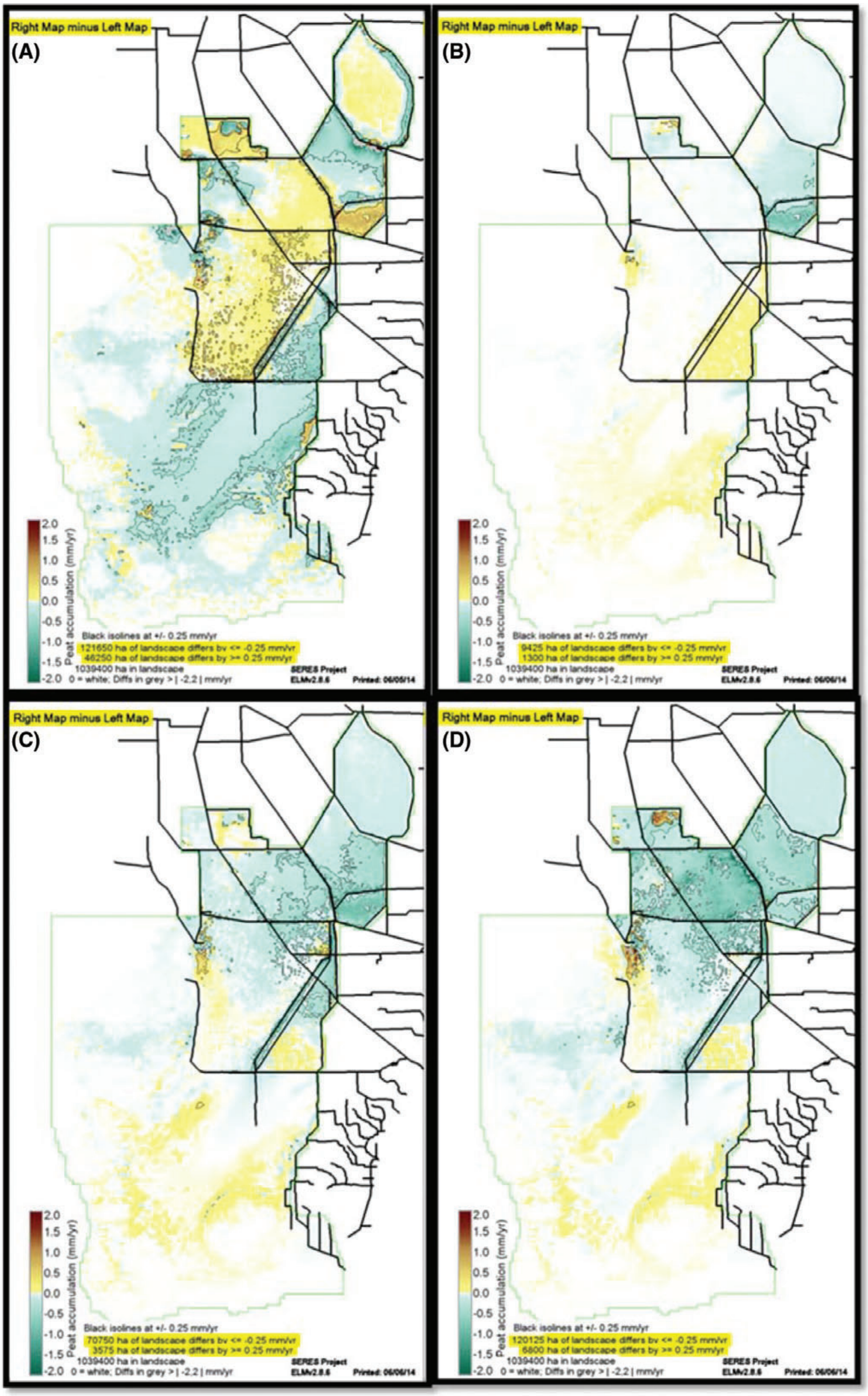

Figure 1. Model run results for soil accretion rates for CERP-ECB (A), PC-CERP (B), ESD-CERP (C), and MSD-CERP (D). Maps represent differences between options and CERP and should be interpreted as follows: for CERP-ECB (A), blue indicates areas where values under CERP are lower than ECB and brown indicates higher values under CERP. For (B), (C), and (D), blue indicates areas where scenario values are lower than CERP and brown indicates areas where option values are higher than CERP.

**Table 2.** Comparison of calculated carbon sequestration potential based on results of ELM model runs for all five hydrologic scenarios.

| | *Area with Soil Accretion Rates (ha)* | | *C Sequestration (tons)* | *Total C over POS (tons)* |
|---|---|---|---|---|
| | *≥0.25 mm/yr* | *≥2.0 mm/yr* | *Per year* | *36 yr* |
| CERP | 845,450 | 95,900 | 107,068,000 | 3,854,500,000 |
| ECB | 846,675 | 116,225 | 114,796,000 | 4,132,700,000 |
| PC | 840,775 | 94,425 | 107,493,000 | 3,869,700,000 |
| ESD | 833,000 | 82,400 | 103,055,000 | 3,710,000,000 |
| MSD | 828,725 | 69,000 | 98,761,000 | 3,555,400,000 |

**Table 3.** Spatial extent (in hectares) of soil P enrichment (both 400 and 500 mg/kg) under modeled scenarios.

| | *Total Area (ha)* | *Total Area (ha)* | *Difference from CERP (ha)* | |
|---|---|---|---|---|
| | *Soil TP > 400 mg/kg* | *Soil TP > 500 mg/kg* | *Soil TP > 400 mg/kg* | *Soil TP > 500 mg/kg* |
| CERP | 492,675 | 191,400 | 0 | 0 |
| ECB | 497,600 | 209,125 | 4,925 | 17,725 |
| PC | 498,200 | 194,350 | 5,525 | 2,950 |
| ESD | 502,875 | 211,350 | 10,200 | 19,950 |
| MSD | 503,050 | 225,825 | 10,375 | 34,425 |

NE ENP and the model-lands that are higher in soil TP under ECB conditions. The difference maps of PC and CERP indicate relatively minor differences between the two scenarios with PC being higher in soil TP in the WCAs with the exception of WCA-3B and very sporadic areas in ENP (Fig. 2). ESD is noticeably higher in soil TP in the WCAs with the main area of soil TP lower than that of CERP is the intersection of WCA-3A, 3B, and NE ENP. This area is also noted as being higher in soil TP under MSD. Soil TP differences between CERP and MSD are very pronounced showing higher levels of P in soils of the WCAs under MSD, with the highest soil TP being centered around the NE corner of WCA-3A along the L-38 canal separating WCA-2A and 3A and eastern portion of the L-5 canal.

### Soil Phosphorus Accretion Rate

ELM model output suggest that under the EBC, 142,000 ha will have a P accretion rate greater than or equal to 50 mg m$^{-2}$ yr$^{-1}$ and 25,300 ha greater than or equal to 100 mg m$^{-2}$ yr$^{-1}$. In contrast, under CERP, 85,975 ha will have a P accretion rate of 50 mg m$^{-2}$ yr$^{-1}$ or more and 8,775 ha greater than or equal to 100 mg m$^{-2}$ yr$^{-1}$. This results in ECB having 56,075 ha more above the 50 mg m$^{-2}$ yr$^{-1}$ rate and 16,125 ha more above the 100 mg m$^{-2}$ yr$^{-1}$ rate (Table 4). PC was found to be very similar to CERP with 84,875 and 8,800 ha above the 50 and 100 mg m$^{-2}$ yr$^{-1}$ rates, respectively, resulting in 1,100 ha less above the 50 mg m$^{-2}$ yr$^{-1}$ rate and only 25 ha more above the 100 mg m$^{-2}$ yr$^{-1}$ rate. Although options D and E do not approach the magnitude of the landscape with high rates of P accumulation found in ECB, these options do exhibit higher spatial distributions than does PR or CERP. ESD was found to have 90,250 ha above the 50 mg m$^{-2}$ yr$^{-1}$ rate as compared to MSD which had 105,550 ha. MSD had an only slightly higher portion of the landscape accreting P at the 100 mg m$^{-2}$ yr$^{-1}$ rate than ESD (9,800 vs. 9,700 ha). These model predictions resulted in very similar landscape proportions above the 100 mg m$^{-2}$ yr$^{-1}$ rate (925 and 1,025 ha for ESD and E, respectively); however, the portion of landscape above the 50 mg m$^{-2}$ yr$^{-1}$ rate for MSD (19,575 ha) was much higher than that of ESD (4,275 ha).

Areas where P accretion rates are noticeably lower under CERP versus ECB include the canal inputs around WCA-1 and 2A, the NW corner of WCA-3A proximate to Miami Canal inputs, and the NE corner of ENP near the C-111 spreader project area north of Taylor Slough (Fig. 3). Similarly to the soil TP models, PC differed much less from CERP than did ECB (Fig. 3B) with PC performing equally or slightly better than CERP in a large portion of the WCAs with the exception of 2B. Most prominent differences are noted in the Holeyland and Rotenberger tracts, an area of excessive P inputs historically.

ESD is noticeably higher in proportion of landscape accreting P at higher rates than CERP (Fig. 3C). Most of this elevated accretion occurs in the WCAs with the highest being in northern 3A along the L-38 and L-68A canals. Areas of higher P accretion by CERP occur in southeastern 3A and 3B along the L-67 canal and Shark Slough in ENP. Similarly, MSD follows the same trends of exceeding CERP in the WCAs, most notably Northern 3A along the l-37 in the same locations as observed in ESD, just to a larger degree. As with ESD, CERP is higher in southeastern 3A and 3B along the L-67 canal and Shark Slough in ENP.

## Discussion

### Soil Accretion and C Sequestration

Everglades organic soils, whose recent history has been a dramatic response to drainage, have undergone subsidence of 1–3 meters in extensive areas south of Lake Okeechobee (Stephens & Johnson 1951; Snyder 2005). Soil loss in the EAA

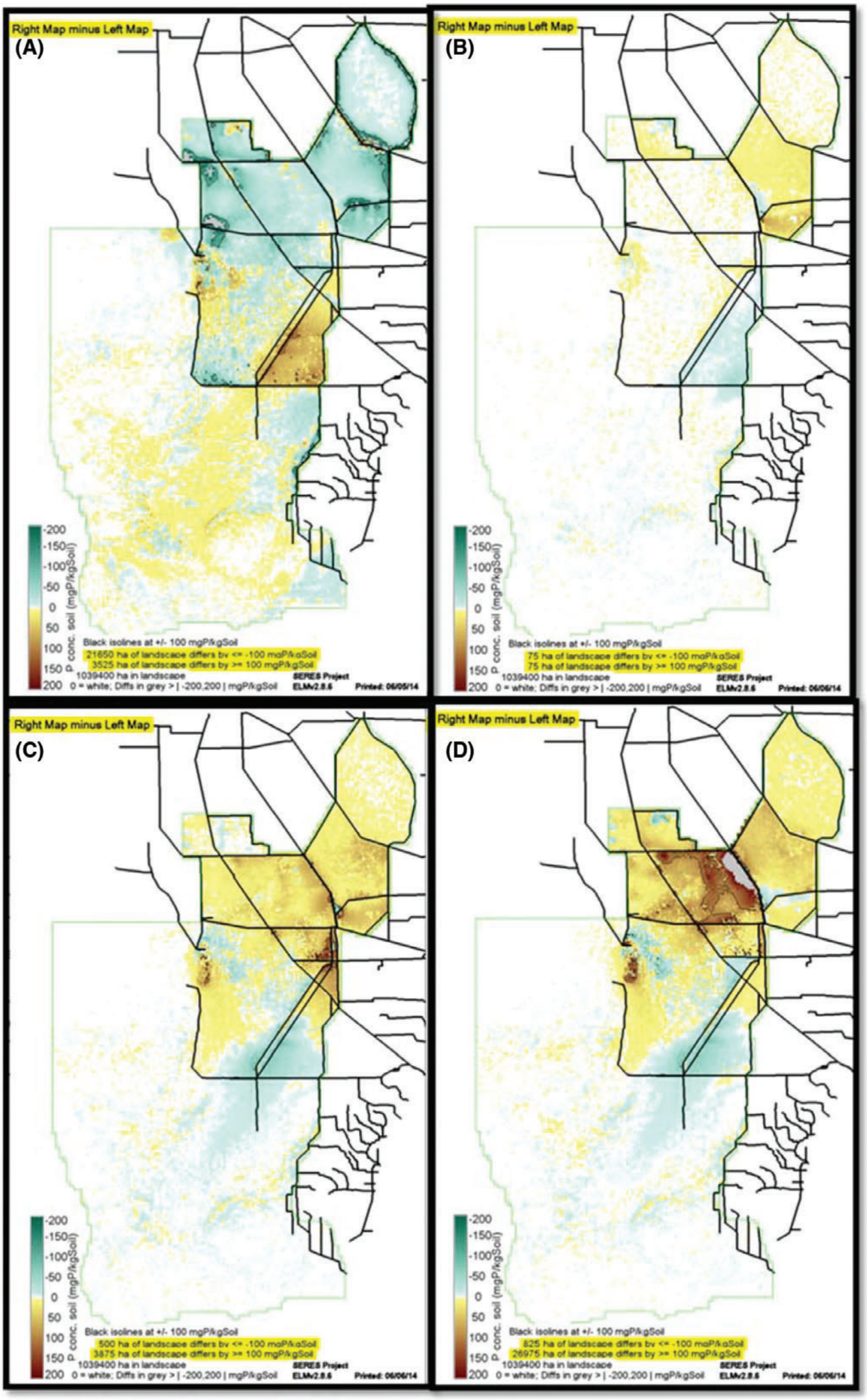

Figure 2. Model run results for soil TP for CERP-ECB (A), PC-CERP (B), ESD-CERP (C), and MSD-CERP (D). Maps represent differences between options and CERP and should be interpreted as follows: for CERP-ECB (A), blue indicates areas where values under CERP are lower than ECB and brown indicates higher values under CERP. For (B), (C), and (D), blue indicates areas where scenario values are lower than CERP and brown indicates areas where option values are higher than CERP.

**Table 4.** Spatial extent of soil phosphorus accumulation rates (ha) under hydrologic scenarios.

| | *Total Area (ha)* $\geq 50\,mg\,m^{-2}\,yr^{-1}$ | *Total Area (ha)* $\geq 100\,mg\,m^{-2}\,yr^{-1}$ | *Difference from CERP (ha)* $\geq 50\,mg\,m^{-2}\,yr^{-1}$ | $\geq 100\,mg\,m^{-2}\,yr^{-1}$ |
|---|---|---|---|---|
| CERP | 85,975 | 8,775 | | |
| ECB | 142,000 | 25,300 | 56,025 | 16,525 |
| PC | 84,875 | 8,800 | −1,100 | 25 |
| ESD | 90,250 | 9,700 | 4,275 | 925 |
| MSD | 105,550 | 9,800 | 19,575 | 1,025 |

has slowed considerably from the rapid rates characteristic of primary subsidence in the first few decades of water withdrawal (Wright & Snyder 2009), but recent surveys indicate that significant soil loss has continued in some nearby portions of the WCAs since the 1940s (Scheidt et al. 2000; Osborne et al. 2011*a*). As with histosols worldwide, subsidence of Everglades organic soils increase with the depth to the water table (Osborne et al. 2014). Stephens and Stewart (1977) suggest that organic soil subsidence increased as a linear function of depth when the water table receded from 30 to 80 cm below the surface, with annual subsidence increasing by about 7 mm per 10 cm increase in depth. Similarly, Osborne et al. (2013) report linear responses in soil respiration with drawdown resulting in calculated rates of subsidence of 1–2.7 cm/year. Based on $^{137}$Cs activities in soil cores, Craft and Richardson (1993) reported a mean accretion rate of 2.3 mm/year in unenriched portions of WCA-2 and WCA-3A. Fastest accretion was found in persistently flooded areas (lower WCA-3A, central WCA-2A) and the slowest was found in over-drained areas (northern WCA-3A, WCA-2B). In the same study, the most rapid organic soil accretion (approximately 4 mm/year) occurred at a P-enriched site within the cattail invasion front in WCA-2A. It has been shown that decomposition exceeds production and soil organic matter is mineralized when the water table is below the organic soil surface, and that organic matter is accreted when water rises toward and above the soil surface (Reddy et al. 2006; Osborne et al. 2014). Further, phosphorus enrichment may stimulate soil accretion, at least in the short run, by facilitating a shift in vegetation toward the faster growing species like cattail (Newman et al. 1997).

In this study, we leverage long-term, multidecadal, organic soil accumulation rate as a cumulative metric over the duration of period of simulation, capturing the net effect of ecosystem responses to P loads and varying water depths. Results of rates less than 1 mm/year may reflect excessive dry-out (and thus organic oxidation), while rates exceeding 2 mm/year may reflect eutrophication (and thus high plant turnover & associated organic accretion).

It is imperative to take into consideration that the ELM model leverages P input significantly with respect to soil accretion rates and thus higher P inputs result in higher soil accretion rates and C sequestration potential. Because of this aspect of ELM, the ECB condition allows for greater net soil accretion than the other options. The trade-off, of course, is P enrichment and the trophic (Gaiser et al. 2005; Trexler & Goss 2009) and vegetative (Davis 1994; Osborne et al. 2011*a*) cascades that are known to occur with elevated P in both water and soil (Noe et al. 2001; Daoust & Childers 2004). It should be noted that 10 ppb TP in the water column used to model CERP will in fact be a lower amount of TP for plant growth; however, legacy P will still be available to promote high levels of primary productivity in areas of soil P enrichment (Reddy et al. 2011). Managers should recognize that the trade-off of high P to maximize soil accretion and thus C sequestration is one with little ecological value; rather, when interpreting the results of soil TP and P accretion rates, we look to soil accretion (C sequestration) for further support of a particular option over another. Although first in order of presentation, it is not intended to serve as a primary determinant of best management option. With P reduction below 400 mg/kg in soils as a prominent management goal, the order of performance for soil accretion/C sequestration is CERP > PC > ESD > MSD > ECB. This assertion considers lower accretion/sequestration concomitant with lower areal TP enrichment to be preferred over high accretion rates. ECB has high accretion rates; however, the high TP and resulting catastrophic shifts in vegetation are not congruent with restoration goals, hence CERP and PC score highest while ESD and MSD (increased levee removal but decreased hydroperiod) incur lower evaluation.

### Soil Total Phosphorus

The ending soil P concentration after long-term, multidecadal period is a cumulative metric over duration of period of simulation, capturing the net effect of P that has been assimilated in the soils (and thus reflects ecosystem eutrophication status). Because the mass of any new input of P is averaged within a 10-cm depth of soil (which may take circa 50 years or more to accumulate), changes in soil P concentration are somewhat masked (diluted) by the overall mass of antecedent P and organic matter in that profile; that is, this metric not very sensitive to low/intermediate levels of P loading. For purposes of evaluation, eutrophication thresholds are considered 400 and 500 mg/kg.

The CERP scenario allows for 4,925 ha less area considered impacted above the 400 mg/kg soil TP threshold than ECB. This is likely attributed to CERP water quality being better under this performance measure as input P is reduced to 10 ppb TP in inflow waters. PC is very similar to CERP with only 5,525 ha, followed by ESD (10,200 ha) at approximately two times the area. MSD is almost equal to ESD with 10,375 ha in exceedance of the TP threshold of 400 mg/kg. With respect to soil TP, areas of known concern such as WCA-1 proximate to the levee canal, WCA-2A, northern 3A along the Miami

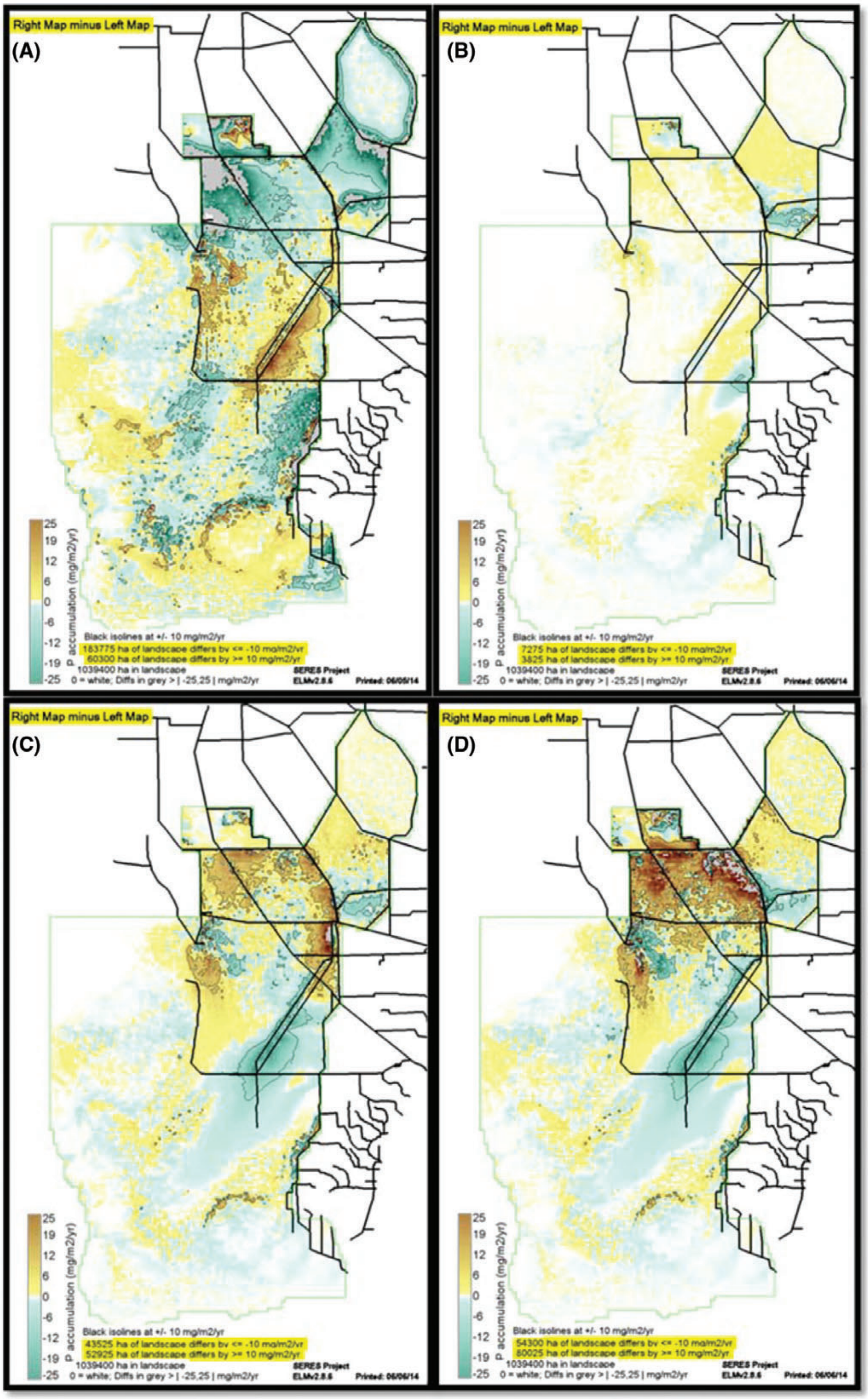

Figure 3. Model run results for soil P accretion rates for CERP-ECB (A), PC-CERP (B), ESD-CERP (C), and MSD-CERP (D). Maps represent differences between options and CERP and should be interpreted as follows: for CERP-ECB (A), blue indicates areas where values under CERP are lower than ECB and brown indicates higher values under CERP. For (B), (C), and (D), blue indicates areas where scenario values are lower than CERP and brown indicates areas where option values are higher than CERP.

and L-37 canals, Holeyland and Rotenberger tracts and the site of the C-111 spreader canal project in northern Taylor Slough (Osborne et al. 2011*a*, 2011*b*) are also sites of notable soil TP in the model runs. Major differences are in central 3A and 3B, to a lesser degree in ENP. It is important to remember that this is a prediction of top 10 cm of soil, which can significantly dilute the effect of P additions to the surface soil. Since all current studies and surveys used this depth, the model is calibrated with this soil depth and therefore not as sensitive to changes here in a 36-year simulation. Using soil TP thresholds, the scenarios are preferred in the following order: CERP > PC > ECB > ESD > MSD. CERP and PC are the most rigorous with respect to balancing restored flow and reduced P loading and thus are preferred. ECB having a longer hydroperiod but higher TP still outperforms ESD and MSD which have lower water TP but also shorter hydroperiods, which exacerbate P enrichment in the long run. Hence, these scenarios were scored less favorable with respect to area of soils exceeding the TP threshold.

### Soil P Accretion Rate

Determination of spatial extent of impacted surface soils via P accumulation rate (Table 4) is a good indicator of process when evaluating scenarios (Reddy et al. 1993). Spatial extent is noticeably higher than predictions of soil TP suggesting this may be better metric for potential change as the rate is not affected by soil volume or depth. In this evaluation, we recognize the management imperative of minimizing the spatial extent of marsh with excessive P accumulation rates, using two risk levels: 50 and 100 $\text{mg m}^{-2}\,\text{yr}^{-1}$. Long-term mean values tend to mask short-term pulses that may have been assimilated by system (hence the model should primarily be used to consider long-term dynamics due to stochasticity of ecosystem).

ECB has 57,125 ha more under the 50 $\text{mg m}^{-2}\,\text{yr}^{-1}$ rate and 16,500 ha more under the 100 $\text{mg m}^{-2}\,\text{yr}^{-1}$ rate for P accumulation in soils than PC. CERP is very similar to PC reflecting the changes in water quality predicted with these scenarios. ESD and MSD, while notably higher than PC and CERP do not approach the magnitude of ECB. P accretion rates are noticeably lower under PR and CERP versus ECB. Areas of concern include the canal inputs around WCA-1 and 2A, the NW corner of WCA-3A proximate to Miami Canal inputs, and the NE corner of ENP near the C-111 spreader project area north of Taylor Slough. This is attributed to changes in WQ and canal flow structures reflect that. We contend that PC is the superior performing scenario when viewed from perspective of soil P accumulation rates with CERP > ESD > MSD > ECB.

This investigation has evaluated several potential restoration scenarios, comparing the existing condition to full implantation of CERP, and three increasingly more complex scenarios. When assessing model output from the ELM, we found CERP to outperform all of the scenarios with respect to soil C accretion (in light of P reduction being a prominent management goal). Incremental implementation of CERP options were found to fall out in the order of increasing complexity being better for soil accretion performance metrics. When viewing soil TP thresholds, CERP again performed best with PC second. However, in this case ECB outperformed the other lesser implementation iterations of CERP suggesting that adding more water with higher P levels is less desirable than less water with respect to P thresholds. Finally, soil P accretion rate analysis found PC to outperform CERP and the other scenarios, ostensibly due to magnitude of P loading. In conclusion, we contend that if possible, the full implantation of CERP be the restoration goal. Other scenarios are notably less well performing in the context of this modeling assessment of restoration and should be considered shortfalls of full implementation of CERP.

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