Can we please be flexible?
Obstacles and opportunities for adaptive management of the Arenal-Tempisque wastershed

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I. EXECUTIVE SUMMARY

The National Invasive Species Council defines the term invasive species as, “a species that is non-native to the ecosystem under consideration and whose introduction causes or is likely to cause economic or environmental harm or harm to humans,” and similar definitions can be found by conservation, government, and non-governmental organizations One well-known example of a native, invasive species is the southern cattail, *Typha domingensis,* in Palo Verde National Park (PVNP), Guanacaste, Costa Rica.

Endemic to pantropical regions, *T. domingensis* thrives in wetlands and is one of the three most invasive cattail species worldwide. Populations were established but controlled in Guanacaste until the 1980’s when the wetland was designated a national park. By Costa Rican law, this removed thousands of grazing cattle. The regime shift that followed covered and hid open water areas used by waterfowl and wading, contradicting the goal of Costa Rican national parks to protect aquatic species and the wetland environment. Despite efforts to manage this invasion via fire, water flow restoration, and mechanical removal, the government has not been able to find a permanent solution. It has, however, begun to reintroduce some cattle into the park.

Whether the significant vegetation composition change is a consequence of the alteration of the hydrological regime and/or local land-use is still a debate in the scientific community. During cattail expansion, *typha* can be both a passenger of change or a driver of change. This respectively means that invasion can be caused primarily by environmental changes with minimal species interaction, or by species interactions with subsequent environmental changes. A lack of a comprehensive understanding of the wetland’s hydrology and the link between ecological degradation (in terms of vegetation composition change) and hydrological alteration is the limiting factor impeding the disproof or validation of the *hydrology-related plant cover changes* hypothesis.

Wetlands are highly dynamic systems characterized by strong feedback effects between (1) the hydrological regime and water chemistry, (2) the type and spatial distribution of flora, (3) and soil properties. Through the use of models, water-use scenarios can be run to assess their impact on the future state of the system, and the uncertainty surrounding these predictions can be quantified, allowing for wiser and more apprised decisions concerning resources and ecosystem management, which is the defining characteristic of an adaptive management approach. It only makes sense that restoration practices should also be studied in the field in terms of their direct and indirect impacts on the wetland’s hydrological regime, and parameterized into the model in order make similar predictions about the state of the system under different land-use management scenarios.

Incorporation of adaptive management strategies to better manage the wetland pose opportunities and obstacles. The use of this integrated, multidisciplinary approach that recognizes uncertainty as an integral component of the decision-making process, can lead to a better control of *typha* spread. The inclusion of this management practice, however, must overcome many obstacles, including numerous resource constraints and administrative law norms. Through a review of adaptive management and governance of the Florida Everglades, recommendations are made as to how best to recalibrate management practices in the PVNP.

II. INVASIVE CATTAILS (*TYPHA DOMINGUENSIS*) IN PALO VERDE NATIONAL PARK, GUANACASTE, COSTA RICA – Elizabeth Ballare

Invasive Species

When we think of an invasive species, it is usually one which overcame a geographic barrier, survived in a new environment, became a self-sustaining population, dispersed and spread, and then caused harm to the environment, animals, plants, and/or humans. However, defining the term 'invasive species' is complex and is guided largely by public perception and interpretation, impacts to human well-being, biogeographical context, and environmental harm.

In 2006, the National Invasive Species Council (NISC) officially accepted the definition of invasive species as outlined in Executive Order 13112 of the Invasive Species Definition Clarification and Guidance White Paper to mean, "a species that is non-native to the ecosystem under consideration and whose introduction causes or is likely to cause economic or environmental harm or harm to humans."[1] While this was meant to curtail the multitude of variants used by professionals,[2] it appears that the subconscious and emotive associations with the term 'invasive' addressed in a 2004 study prevail.[3] Indeed, ecological societies continue to refer to some species as 'exotic pests'[4],and the International Union for Conservation of Nature, the European Alien Species Information Network, The Transnational Policy Network on Invasive Alien Species, the European Union, and the Ramsar Convention all refer to them as 'alien.' [5;6;7;8;9;10]

Along with its definition, the NISC and the Invasive Species Advisory Committee (ISAC) adopted a set of principles for further clarification and included them in the Executive Summary of the National Invasive Species Management Plan (NISMP). Guiding Principle #1, for example, states that, "many alien species are non-invasive and support human livelihoods or a preferred quality of life."[11] The common potato (*Solanum tuberosum*), for example, was first domesticated in modern-day Peru and Bolivia between 8,000 and 5,000 BC and is now enjoyed in Asia, Africa, Europe, and the Americas as a staple crop following a long history of colonization and cultivation.[12;13]

The NISC and ISAC also noted that in order for a species to be considered invasive, the species must be invasive in one area but not another. Oriental clematis (*Celastrus orbiculatus*) was first introduced in North America in 1886-87.[14] After being renowned for its beauty and considered an ornamental by the Arnold Arboretum in Boston, Massachusetts, the plant escaped cultivation and spread wildly in the 1900's. Although it is considered intrusive in the northeastern United States, as well as Idaho, Nevada, Utah, New Mexico, and Colorado, it is considered an invasive species only in Colorado[15] because of its dramatic spread and displacement of native plant species.

Additionally, the species must have some environmentally deleterious effect, either directly or indirectly, usually resulting in a regime change by outcompeting native species populations, altering floral and faunal communities, and even modifying the ecological processes of a native species. These can also be associated with human economic distress which continues today in Australia for example, as a result of the introduction of the European rabbit (Oryctolagus cuniculus) in the 18th century with the First Fleet. Originally bred as food, they escaped and proliferated. After only a few decades, a newspaper article in Tasmania noted "...the common rabbit is becoming so numerous throughout the colony that they are running about on some large estates by the thousands."[16] They are still considered the most significant known factor in species loss in Australia, eating woody and non-woody plants, causing soil erosion, and costing millions of dollars in crop damage every year.[17]

The ISAC also elaborates on impacts to human health as in the current case with Zika[18]; on natural resources such as a decline in timber, soil fertility and stability[19], and decreased carrying capacity[20]; on recreational opportunities such as the decrease in property values[21]; and on altered business opportunities.[22]

The explicit definition of an invasive species in Executive Order 13112 as "likely to cause harm" is contradictory with, for example, the mosquito fish (*Gambusia affinis*), which although detrimental by negatively impacting native insect, fish and amphibian species[23;34] is also beneficial in controlling larval mosquitos.[25]

The five sources listed at the end of paragraph two are in agreement that invasive species are non-native, but other sources disagree.The Sambar deer (*Cervus unicolor unicolor*) in New Zealand[26], and the White-tailed deer (*Odocoileus virginianus*) in North America[27], for example, are native species that have overpopulated natural ranges, and East African couchgrass (*Digitaria abyssinica*) is a native species that forms dense 'grassmats' suffocating other plants and is considered the most troublesome weed in the crops of Ethiopia, Kenya, Uganda and Tanzania[28]. Thus, the argument that, in addition to non-native species, native species can also be invasive, is valid. In 2004, Pysek et. al.,[29] addressed this suggesting that species which increase their distribution and colonize new habitats in a geographical area where they are native should be called expansive, and not invasive, species. However, there appears to be no consensus to date.

Typha domingensis

Another well-known example of a native, invasive species is the southern cattail, *Typha domingensis*[30] which is limited to pantropical latitudes and can be found on all major land masses except Greenland and Antarctica (Figure 1). Likely spreading from Europe through colonization, this semi-aquatic, perennial plant is now one of the three most widespread cattails in the world.[31] It germinates best with fluctuating temperatures and sunlight and can withstand periods of intense drought as well as flooding. One evolutionary advantage of this plant is its rhizomatic nature, the modified subterranean stem of a plant that sends out roots and shoots from its nodes. Thus, even when one plant above ground appears to be dead, it is actually part of a larger underground structure and continues to receive oxygen and nutrients such as nitrogen and phosphorous.

A 2016 analysis of the phylogenetics and phylogeography of *T. domingensis* revealed a wide and steady dispersal between Europe and Australia and the possibility of a new non-native strain in North America. Combined with current sales from over 70,000 websites, this dispersal and hybridization only exacerbates the plants invasiveness.[30]

T. domingensis is considered an introduced and invasive cattail in Hawaii, Florida, California, and Costa Rica.[30] It is problematic in wetlands around the world including, but not limited to, the Great Lakes[32]; the Middle Patuxent Subwatershed in Chesapeak Bay, Maryland[33]; and Palo Verde National Park in Guanacaste, Costa Rica.[34]

Palo Verde National Park

Palo Verde National Park (PVNP) is one of the most ecologically important and diverse wetland complexes in Central America. Located in the Tempisque Conservation Area in Guanacaste Province northwestern Costa Rica (Figure 2)[34], PVNP is home to more than 400 animal species[35]. Vegetation is dominated by a tropical dry forest (well-defined and acute seasonal flooding and drought) with essential marshes, flood plains, and seasonal pools. The habitat receives approximately 1.5 m of annual rainfall[36] and also includes dry deciduous, spring, and riparian forests, as well as savanna, mangroves, and wetlands.[37] The PVNP wetland was privately owned and operated as a hacienda by the Stewart family between 1923 and 1979[38], at which time almost 20,000 cattle were rotated between wet and dry seasons in the uplands and adjacent pastures. Inhabitants also enjoyed some agricultural production and forested land use.

In 1975, approximately 15,000 hectares of the Tempisque was expropriated from the Stewart family by the Costa Rican government as part of a settlement program[39] and under Executive Decree No. 6942-A, part of those expropriated lands were designated a national wildlife refuge in 1977. In 1980, Palo Verde was converted to a national park which, by Costa Rican law, prohibited residential and pastoral use of the land. The elimination of cattle grazing, along with a decade-long flood, a road impeding water flow from Quebrada Huerton into the wetland, and drastic fires caused a regime shift in the Palo Verde Marsh and enabled *T. domingensis* to dominate the landscape.[40;41;42] This shift rapidly changed a heterogenous landscape with open water and primarily short vegetation into a vast and sprawling cattail monoculture[43].

In 1991, Costa Rica ratified the Ramsar convention on wetlands of international importance, including Palo Verde within the Ramsar list. It was, however, moved onto the Montreaux list in 1993 because of the dramatic changes the landscape had incurred and decline in overall species richness and density.[38] Of particular concern is the inability of waterfowl and wading birds to locate the watershed for use as a stopover point due to the overgrowth of *T. domingensis*. This proliferation obscures open water areas, forcing these animals to go to other areas that are not protected and possibly less nutrient rich. This is in opposition to the goals of Costa Rica's National Park Law of protecting aquatic species and the wetland environment within it. [7] The declining condition forced the government to perform active management of wetlands to ensure open water spaces and proper functionality.

Active Management Attempts

Since the problem began in the mid 1980's, there has been a roughly 35% decrease in wetlands as a result of *T. domingensis* invasion. [44] Along with park rangers and scientists, the Costa Rican government has attempted to mitigate the damage done by this plant. Prescribed fire management, attempted in the 1990's was deemed too unsafe. A channel was created to restore the flow of water from Quebrada Huerton, which has improved the situation to a degree. The most notable difference has been the use of a machine called a fangueo. This machine is used to flatten and remove *T. domingensis* [34], and a 2014 Research and Monitoring Program of the Arenal Conservation Area Tempisque census shows that water fowl increased from 1,300 to over 22,000 as a result.[44] Although there has been continued increase in bird species diversity and richness, a 2011 study by Osland et al., showed that while effective for rapid removal in the short term (1st year), the fangueo does not affect the resiliency of the plant, which returns with higher species richness in years 2-4. [34]

The reduction in cattle grazing is often accredited as being the primary cause of the 1980 regime shift and subsequent Typha expansion. Because cattle trample vegetation and eat young *Typha* shoots, they likely prevented competitive exclusion within the landscape [43;45]. Indeed, this phenomenon has been recognized in other wetlands, including Australia and India [46], and Osland et al., 2011 showed that areas with cattle grazing had lower *Typha* density than those with no management or the use of only the fangueo. [34]

Although the use of the fangueo has made a marked difference, the Costa Rican government appears to recognize the need for a long-term, more permanent solution and the correlation between the removal of cattle and the proliferation of *T. domingensis*. A management plan implemented by the Tempisque Conservation Area, Guanacaste, allows some controlled cattle grazing in parts of the country [47;48] including PVNP. There, cattle owned by workers who bring their cows to the area during work hours are allowed to graze in the marsh [38] and neighboring Reserva Biologica Lomas Barbudal. [49]

Given the results of Osland et al., and others, and the apparent willingness of the Costa Rican government to use cattle grazing as a management tool, we posit that the reintroduction of larger scale cattle grazing plays a central role in the long-term solution and is worthy of consideration. In the chapters that follow, we elaborate on this further and suggest a change in policy citing examples as precedent.

III. WHY PARAMETERIZING MANAGEMENT PRACTICES IN PALO VERDE'S HYDROLOGICAL MODEL? – Pierre Sosnowski

Introduction

Management techniques such as the use of fire, grazing, cutting with machete and the combination of them have been tried to stop the cattail expansion in Palo Verde National Park (PVNP). Fangueo, a technique used in rice paddies was adapted to crush and disk the cattail under water. This method is effective in delaying Typha regrowth for a few seasons but is expensive and produces short-term results.

McCoy (1994) [50] and D. A. Stewart, who respectively have intensively studied and worked with cattle in PV Lagoon for more than 50 years, disagree on fundamentals such as whether cattle actually consume cattail or not. [51] Yet, The attempt to restore the Palo Verde lagoon through the reintroduction of cattle in 1991 (500 head of cattle – 1 cow per ha) has been implemented without conducting a systematic experiment to evaluate the impact and changes they may cause in this ecosystem. [51] The lack of any evaluation and understanding of long-term effects on the system can also be said of the practice of Fangueo.

Hydrology is probably the single most determinant of the establishment and maintenance of specific types of wetlands and wetland processes, but biotic components are active in altering the wetland hydrology and other physicochemical features. On the other hand, wetland soils are both the medium in which many of the wetland chemical transformation take place and the primary storage of available chemicals for most wetland plants. [52]

The physical properties of the soils that determine their ability to sustain plant growth are those that determine the extent of root proliferation as well as air, water movement and water storage. [53] Soil desiccation, soil compaction, soil erosion and water infiltration are combined processes affecting plant growth. [53]

Soil structure may be affected either by mechanical stress or by hydraulic stress from natural wetting and drying cycles. [54] Stock trampling along with machinery affect soil depending on (1) trampling intensity; (2) soil moisture; (3) plant type; (4) field slope and (5) land use type. In our study case, field slope and land-use types are likely negligible factors. Trampling-induced compaction is characterized by its spatial heterogeneous distribution [54]. In addition, the depth of compaction induced by pugging depends on (i) animal weight; (ii) soil moisture; (iii) hoof size and (iv) kinetic energy.

The most commonly used parameters to demonstrate the occurrence and effects of soil compaction are (I) bulk density (BD) and total porosity; (II) macroporosity; (III) penetration resistance (IV) air permeability; (V) saturated hydraulic conductivity K_{sat}; (VI) pre-consolidate pressure (VII) dye surface density and (VIII) infiltration capacity. [54]

Furthermore, in invaded systems, the initial driver of environmental change may be anthropogenic, or it may be the invader itself; and the mechanism behind native species decline may be the human-induced environmental change, competition from the invader, or invader-induced environmental change. [55]

In other words, Typha spread could have resulted from (I) a change in hydrological conditions:

(Ia) lethally affecting other species, meaning Typha didn’t get any more competitive; it simply enjoyed the newly free space;

(Ib) favoring Typha development without any effect on other species, but allowing Typha to outcompeting them;

Resulting from a change (IIa) in the quality or quantity of water entering the system (e.g. through altered Tempisque river discharge); (IIb) from a change in the system physical characteristics itself (e.g. through mechanical disturbance), affecting the water partitioning and chemical reactions taking place; (IIc) or both.

Finally, (III) the contribution of external drivers of change on Typha spread could be relatively insignificant as opposed to strong positive feedback effects Typha has on its own development, for example through nutrient-rich litter production, reducing light levels and obstructing growth of other less competitive species. [56]

Given the intertwined links between soil properties, water partitioning and plant growth in PV wetland, for management purposes, the adopted hydrological modeling approach should provide means of elucidating hydrological responses to not only water-use scenarios, but also management practices scenarios. In addition, the link between hydrological alteration and ecological degradation should be deepened and translated into computable indicators.

However, for the effort of parameterizing management practices in a mechanistic spatially-distributed hydrological model of PV’s wetland hydrological partitioning to make any sense, one should also explore the timeframe of the regime shift and try to answer the million-dollar question: what was the main driver of Typha spread?

Effectively altering the Vertisols engineering properties

Laboratory experiments [56] revealed there was an optimum moisture content above which dry BD, penetration resistance[1] and shear strength[2] decreased with increases in compacting effort. Crack length, depth and width of the Vertisol increased with increase in the static pressure applied, and with increases in the number of days of drying. Crack length and width had the greatest influence in the loss of moisture.

On Ethiopian self-mulching Vertisols, effect of livestock on soil resistance to penetration was also significantly higher in the heavily grazed plots, but in a specific soil moisture range for flat ground (0-4% slope). Under and above a certain soil water content, soil resistance to penetration was only slightly more important in the heavily grazed plot as opposed to the non-grazed plot. [53] Although they tended to disappear with the onset of the rainy season in all plots,

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[1] Soil resistance to penetration is used as an indicator of soil sealing

[2] The shear strength is the load that an object is able to withstand before it fails in shear in a direction parallel to the face of the material, as opposed to perpendicular to the surface.

greater crack width in the cracking pattern was also observed in the heavily grazed plots than in medium and non-grazed plots. Finally, in heavily grazed plots, moisture content was also lower as well as infiltration of accumulated water to the soil matrix.

This highlight how the wetness status of the wetland can influence the effectiveness of the management practices. In our case, according to [53], [56] there exist a maximum soil water content above which management practices would be counter-productive as BD and soil resistance to penetration would be lowered again, and a minimum soil water content below which (see [53]) trampling would not be as effective in increasing BD. This is because Depending on its water content, a highly clayey soil may appear in one of four states: solid, semi-solid, plastic and liquid. Depending on its state, its engineering properties will also vary, such as its resistance to compression and shear load.

This means that the wetland's present and immediate future wetness status should be known for more effective planification of mechanical disturbance.

Effectively impeding Typha growth and survival

Typha's phenological status and hydrology-induced physiological stress can significantly influence the effectiveness of management practices. Apfelbaum (1967) provides a review of different management approaches experimented for Typha reduction. [57] Most studies show that depending on the period of submergence (amount of time under water), the timing (period of the year), the water level and the recurrence of the management method, success rates were very different.

Some examples are that Typha stores large carbohydrate energy reserves in rhizomes to produce new ramets and recover from disturbance. Reserves are built up during the growing season and stored through the winter to provide food during the period when the new aerial shoot develops in the spring and early summer, therefore underlining the importance of the timing of submergence. [58]

Cattails also transpire significant quantities of water (2-3 m of water/acre/year), exacerbating the importance of hydroperiod in the development of the species. Potential evapotranspiration can be computed based on meteorological data. Therefore, an effective level of flooding for cattail control must account for evapotranspiration losses of water (thus the meteorological conditions and *Typha* abundance). [57]

Whether cattle forage on young Typha seedlings has not been proven in any consulted study. However, studies have shown that flooding of clipped Typha stands resulted in rapid decay of below-water biomass consequently to the interruption of the gas exchange supported by live and dead stems reaching above the water's surface. [57], [58]

Previous work about management impact on the PV wetland system and its limitations

Fangueo

Work has been done in Palo Verde to assess the impact of Fangueo on cattail development, species diversity and water ponding. [60], [61] However, little work has been done to assess the impact of this practice on soil physico-chemical properties, and no work relates these changes to changes in water partitioning.

Florencia Trama [61] quantified the change in plant cover, specie richness and abundance of individuals and the response of aquatic birds to the restoration treatment. She established 3 plots of approximately 80ha each, two managed with Fangueo, and one control plot without Fangueo management. She used remote sensing products to quantify the change in vegetation, and counted the birds occupying the plots on a regular basis. As a result, cattail cover decreased from 35% and 62% to 9% and 7% in the plots under Fangueo activities, while in control plot the percentage was always higher than 60 %. A maximum of 62 aquatic bird species, 70 % of the total aquatic bird species for this wetland, were registered in 32 samplings. She also found that species richness, abundance of individuals and species diversity were lower in the control plot [62].

Florencia Trama's work rigorously quantified the effective and dramatic impact of Fangueo on avian visitation, aerial cover classes and the creation of desirable avian habitat in PVNP. The work however doesn't try to assess the mechanisms through which the practice influences the water ponding, development of cattail and the practice's effectiveness dependency on soil moisture. It thus cannot be integrated in a process-based hydrological modeling approach.

Osland et al. (2017) also used applied *Typha* removal treatment at three levels: control (C), Fangueo (FF), and Fangueo with fencing (FF) to exclude cattle from grazing. [60] Nevertheless, in their investigation, they assessed the physical disturbance and potential compaction associated with Fangueo, by measuring soil physical and chemical properties. Compaction was assessed through measurement of BD at the different plots. They found no apparent long-term impact of Fangueo on soil BD or seed bank germinant composition. However, some critiques can be formulated concerning the methodology undermining this conclusion: (i) only two soil samples were collected at each site, thus neglecting soil heterogeneity (80ha plots) and (ii) the study doesn't mention anywhere whether BD was measured at the same water content. This suggest that while they mentioned the shrinking-swelling behavior of the soil, they did not consider the changes in BD with water content. If not compared at the same water content, bulk densities differences between plots will not provide any insight about the relative influence of Fangueo on soil compaction; (iii) finally, BD accounts for the changes in the volume of voids of soil under consideration, but it cannot account for the changes in volume distribution of these voids, or changes in their connectivity. Therefore, at a given BD, for the same soil, the pore geometry and continuity can differ. BD alone is an indicator of soil compactness, but not always its effects, particularly in respect to transport properties. [54] Indeed, studies have shown that Vertisols can undergo a lowering of their infiltration capacity while resisting compaction through shearing and churning of the soil surface by cattle trampling. [63]

One appreciable feature of the study however is the evaluation of the effectiveness of Fangueo on *Typha* development at different seasons and water-depth, thus indirectly accounting for the plant's phenology and the influence of hydric stress on management practice's effectiveness.

Cattle Grazing

From the Organization for Tropical Studies database, only one study on the effect on management techniques including cattle grazing in Palo Verde seemed relevant for this paper. This study [50] is unfortunately unavailable. We will therefore base ourselves on work achieved elsewhere on the mechanical impact of cattle grazing on the seedlings destruction and soil disturbance and its other means of influence on *Typha* development to suggest how such a management practice can be parameterized into hydrological models.

Direct impact on plant growth also include damages from trampling, whereas indirect influence is through soil compaction/loosening affecting rooting capability. Compaction or loosening of the soil will also influence soil microtopography (thus water local runoff) and soil infiltration capacity. The importance of these impacts are a function of stocking density, and separation of trampling and forage consumption effects become important if one compares stocking systems in which the distances traveled for water are radically different. [63] Stock concentrations around water sources are often greater, and thus one might expect soil disturbance per unit of stock density or forage consumption to be greater. [63] This is likely the case in wetlands with sparsely distributed water ponds such as the Palo Verde lagoon.

Therefore, their suggested approach would be:

- (i) To quantify whether and how trampling affects infiltration;
- (ii) To quantify changes in soil infiltration capacity as a function of stocking density;
- (iii) To quantify plant destruction through trampling as a function of stocking density;
- (iv) To relate stocking density (cow-years ha^{-1}) to the intensity of trampling (density of hoofprints m^{-2}) by considering distances and spatial patterns of animal travel;

Connection of stocking density to landscape-scale pattern of trampling intensity allows to scale up impact of trampling from a plot- to landscape-scale.

Following the approach of Dunne et al. (2011) [63] for characterizing trampling heterogeneity, there could be two means for quantifying the effect of trampling on hydrodynamics:

1) By experimentally measuring in the field soil hydraulic conductivity (K) (using double-ring infiltrometers such as in [62]) at different distances (r) from the water source and at different initial water content, allowing for interpolation and extrapolation of measurements;
2) By measuring the effects of the force produced by a hoof on the soil under laboratory conditions [64], or based on literature reviewing static pressure applied by hooves of cattle of different size and weight, and quantifying under laboratory conditions the evolution of soil resistance to penetration and BD to different static pressure applied (using Proctor Compaction blows, see [56], [65]) at different moisture content. Then, using hydromechanical modeling approaches like modeling the relationship between soil BD and the soil water retention curve (SWRC) [66], one could take into account trampling-induced BD increase in water transport modeling.

IV. ADAPTIVE MANAGEMENT IN PALO VERDE NATIONAL PARK, GAUNACASTE, COSTA RICA – Melissa Dangond

Resilience in Palo Verde

Resilience is the ability of an ecosystem to absorb change and respond to a disturbance by resisting damage and recovering quickly. [73] When an ecosystem surpasses its threshold, the point at which a small disturbance causes a rapid change in the ecosystem, the ecosystem may not be able to return to its original state through its inherent resilience. [73] When this happens, a regime shift has taken place. [73] Regime shifts happen in all kinds of ecosystems and are expected to increase as human influence on the planet increases. [74] They occur when the dominant structural features of an ecosystem, feedback loops, are replaced by alternative ones. [75] These non-linear changes are seen as ecological crises that can substantially affect the flow of ecosystem services that humans and animals rely upon. [75] Such crises may unveil failures in approaches used for policy and management. [75]

Whether Palo Verde National Park has experienced a regime shift is up to debate. Some argue that it has gone from a "pasture and wet prairie to a cattail dominated savannah-like wetland." [76] Regardless of whether we title this a "regime shift" or not, it is apparent that significant ecological changes have occurred in Palo Verde (PV). The increase in typha growth, since PV's designation as a national park, has reduced the open water habitat and has compromised what was once an important nesting site for migratory birds. [77] This "regime shift" has been attributed, in part, to the removal of cattle grazing from the landscape. [77] Prior to its designation as a national park, PV was a hacienda used for intensive cattle ranching. [77] When PV was designated a national park, the grazing was prohibited. [78] Article 8 of the Costa Rica National Parks Law explicitly prohibits the grazing of cattle. [79] The notion that human activity always harms ecosystems is outdated and human activity seems to have a correlative relationship with the ecological status of PV. Human activity, specifically cattle grazing, seems to be positively correlated to the status of the wetland as an important nesting site for waterfowl. This, however, is a mere hypothesis and cannot be definitively determined.

As typha colonized the wetland, open water areas diminished, and less and less migratory birds used the area for nesting. [80] Instead, the waterfowl began trespassing onto the rice paddies and sugar cane farms in the area surrounding the park. [80] Due to its historical importance to birds, new management strategies were implemented to deal with the uncontrollable typha. [79] In 1998 the environment ministry began a program of "active management" including the experimental re-introduction of cattle. [81] In addition, fangueo, a tractor with blades, is used to cut typha and a channel was constructed to restore water flow from the Quebrada Huerton. [82; 83]

The re-introduction of cattle was accomplished by overlooking the Costa Rica National Parks Law and relying instead on international law. [76] This is possible because of the monist system of Costa Rica, where international law trumps domestic law. [76] One of the results of the Ramsar Convention was the "Wise Use Doctrine." [79] This doctrine states that "[w]ise use of wetlands is the maintenance of their ecological character, achieved through the implementation of ecosystem approaches, within the context of sustainable development." [84] This emphasizes that human use on a sustainable basis is entirely compatible with Ramsar principle and wetland conservation in general. [84]

By combining the “wise use doctrine,” current management practices, experimentation, and modeling, the PV wetland may have a chance of becoming the important “pasture and wet prairie” it once was for migratory waterfowl. Through the use of adaptive management and adaptive governance, flexible management policies can be incorporated that use experimental data about thresholds and feedback loops to adjust management decisions accordingly. [85] In the end, a lack of human intervention may kill the wetland and more human intervention may save the wetland.

Adaptive Management and Adaptive Governance

Adaptive management (AM) has come to the forefront of ecology and environmental law in recent years. It is an iterative and integrated, multidisciplinary approach that is used by many U.S. federal resource agencies, as well as many state and local land managers. [86] AM recognizes that natural resources will always change and, therefore, sees uncertainty as an integral component of the decision-making process. [87] In order to reduce uncertainty, AM relies on experimentation and learning, through system monitoring, rather than through the elimination of variables. [87] As scientists learn more about the systems, policies are adjusted to conform with the new knowledge.

Adaptive governance (AG), or resilience-based governance, is a way to incorporate AM into governance. This method of governance “supports the integration of diverse, multilevel, formal institutions, informal groups or networks, and individual stakeholders for collaborative environmental management that incorporates [AM] principles in a nested, overlapping system.” [88] It is a framework used to analyze social, institutional, economical, and ecological foundations of multilevel governance modes that are successful in building resilience for the challenges posed by global change, and coupled complex adaptive socio-ecological systems. [89] It encompasses a broad set of institutions, norms, and processes that arise in cases where there are institutional failures in natural resource management and governance. [90]

AM and AG provide many opportunities for environmental regulation and management. Because of its integrative nature, AG promotes the use of adaptive assessments, experiments, models, scenario planning, and stakeholder participation. Through such integration, people with different interests, skill-sets, and mind-sets come together to come up with ideas that can be combined to produce more effective management policies. Because of the diverse knowledge (scientific, legal, anecdotal, etc.) required for environmental regulation, such a collaborative and integrative method that incorporates a variety of experts and promotes innovation seems to be the best way to effectively protect ecosystems and the goods and services they offer.

AM and AG are especially useful when evaluating the complexities of trade-offs among ecosystem goods and services. [91] Because systems like the PV wetland are complex with various interdependent factors, changes to one or more factors can trigger non-linear changes in the entire system. This can have deleterious effects to the ecosystem goods and services that we rely on. AG acknowledges this and tries to reconcile the uncertainties associated with the management of such services. [86] This means that management strategies cannot be static and must evolve in response to new information. [85]

Unfortunately, many constraints hinder the implementation of AM and AG. This is mainly due to the centralized, top-down administrative structure of environmental protection, and the slow-moving and change-resistant nature of bureaucratic systems. [92] When discussing constraints, we will focus on those in the United States, which can then be applied to other legal systems.

The most prominent constraints to a successful integration of AM and AG are resource constraints, the centralized nature of federal environmental law, statutory requirements, administrative law norms, and constitutional issues. [93] Due to the iterative and ongoing nature of AM, it is much more resource intensive than conventional, top down regulation. [94] Because of this, AM places a high demand on financial and personnel resources – something that is already lacking in environmental agencies. [94] Furthermore, most environmental problems are manifested at the local level. Federal statutes, however, impose uniform environmental standards without much accounting for regional variation in environmental conditions and local priorities. [95] Also, statutes rarely authorize AM explicitly. [96] When agencies have adopted adaptive strategies, it has been through exploiting ambiguities within statutes and finding room for interpretation. [96;97] In order for agencies to adopt AM, legislatures must empower them to do so through statutory reform, and even then, these statutes are subject to citizen suits and judicial review. [96] Administrative law norms also require agencies to conduct up-front analysis of potential courses of conduct and these agencies are expected to explain the basis for their decisions – this leaves little room for the meaningful experimentation required by AM. [98] Finally, the US Constitution places a great emphasis on due process of law which requires adequate notice. Legal certainty and predictability make it possible for members of the public to know and predict what is legal and illegal – notice. [97] As Adler (2015) suggests, “granting agencies the authority to engage in true [AM] raises the specter of an unchecked branch of government with the power to alter laws anytime it desires.” [99]

Because of all these constraints, if the implementation of AM is to be effective, it will require an increase in resources devoted to research and information gathering, and fostering greater local experimentation with environmental management through a “polycentric” approach. [100;101] While the statutory constraints are a real impediment in the United States, in Costa Rica they are less of an issue. Due to Costa Rica’s monist system, this constraint can be overlooked by using direct language from RAMSAR. However, statutory reform that incorporates the use of AM and AG can only help. Because PV is a national park, and therefore owned by the government, the notice and due process issues are much easier to navigate through than if the land was private property. Furthermore, Costa Rica’s fragmented government may pose more or less of a threat to the incorporation of AM, but this must be investigated further.

Outdated Approaches

Two approaches to environmental and ecological regulation predominate the legal field: front-end management (FEM) and balance of nature (BoN). FEN is characterized by simplified predictions of environmental harms, costs, benefits, and ultimately the finality of process. [73] It looks to predict how ecosystems will behave in a very simplified manner. BoN is a concept that describes natural systems as being in a state of equilibrium. It infers that the natural state of a system is the preferred state and that it is best to leave the system undisturbed. Ecosystem management is most often based on these two concepts – they try to create policies that manage systems to sustain or optimize balance through regulation. [73] Article 8 of the Costa Rica National Parks Law is a perfect example of these two concepts: it prohibits cattle grazing because it assumes and predicts that human intervention disturbs the equilibrium of the system. The problem is that these concepts are much too simplified to be applied to complex systems like PV. There are too many interdependent factors and uncertainties to be able to make a simple prediction as to how the system will react in response to change. Also, the BoN assumption is not relevant for systems that can be pushed across thresholds and experience regime shifts. [87] By segmenting ecosystems into different management components, you ignore the interdependent and cross-scale nature of those ecosystems. [87] Finally, even with Article 8 in place, humans continue to affect PV. Agriculture in PV's surrounding areas cause fertilizer run-off and tilapia farms cause endocrine-disruptor run-off. So, in reality, while laws like Article 8 aim to adhere to the BoN assumption, they really do not prevent human intervention. Because of this, and because there are positive ways to incorporate human intervention (like cattle grazing, fangueo, and the construction of a channel to increase water-flow to the wetland), using these concepts in regulation is outdated and ineffective.

Adaptive Management and Adaptive Governance in Other Ecosystems

The Florida Everglades

Many places in the world have used AM and AG in complex resource systems. One example is the Florida Everglades. Here, AM was applied so that managers could address and resolve inherent uncertainty associated with meeting social objectives, specifically ecosystem scale recovery. [75;86] In the following paragraphs, we will first look at the history behind the incorporation of AM in the Everglades, how AM has been applied, and whether or not it has been successful in Everglades management and restoration.

By the end of the 1980s, the Everglades was experiencing an increase in endangered species, spreading invasive species, changes in landscape patterns, decline in wading bird nesting, and loss of soil formation. [102] This decline in ecosystem services set the stage for the comprehensive ecosystem restoration efforts that we see in place today. [103] In response to the realization of the 1980s, Congress adopted The Comprehensive Everglades Restoration Plan (CERP) in 2000, which mandates that the ecosystem restoration process be done through an AM protocol. [102;104] This, however, came after two decades of conflict and controversy, including Governor Graham's "Save Our Everglades" program and the litigation that ensued when the U.S. State Attorney sued the State of Florida in 1988 to stop the flow of phosphorous and other pollutants into the Everglades. [103;104]

Before CERP, many initiatives and restoration projects were well underway, like the Everglades assessment, which was performed by a small group of scientists from 1989 to 1991. [102] The workshop was cross-sectoral, learning based, participatory, and polycentric, and resulted in a computer model developed to articulate hypotheses that led to the decline in ecosystem services. [102] Regardless of its ephemeral nature, the workshop opened the possibility of alternative management approaches. [102] After this workshop, the U.S. Army Corps of Engineers worked with the District to produce the "Central and South Florida Comprehensive Review Study" of 1999, which incorporates an adaptive management and monitoring plan, and which CERP is highly based on. [105]

With the adoption of CERP came the adoption and evolution of AM. New projects were implemented, including the Modified Water Deliveries to Everglades National Park Project (Mod Waters) and the Decompartmentalization Project (Decomp). (Light) These ongoing projects provide insights to how AM has evolved in the area and provide useful generalizations for other ecosystem restoration projects. [106]

Mod Waters shows the divergence of interests of different federal agencies. [106] The agencies different missions have caused disputes and even led to litigation in some instances. [107] However, on the state level, public servants have come together to make important decisions like denying Miami-Dade's request for additional water supply from the Everglades. [107] Because of this, Light (2006) suggests that "public servants in the Everglades Restoration effort seem better able to use state institutions as opposed to federal institutions to implement AM projects." [107] This coincides with suggestion from Adler (2015). [95] Another insight from the projects mentioned above is that these projects are ongoing and can be seen as experiments in adaptive management. [106] Most of them have been done in increments, or "phases," so that later phases can take advantage of the knowledge acquired in the earlier phases and respond to limitations. [108] By using incremental phases in these projects, we can learn how to best recalibrate policy to adhere to AM criteria. Finally, these projects highlight the importance of agency empowerment through legislation and suggest that more flexibility must be given to agencies in order to truly learn by doing. [109] CERP and Florida law require these projects to be in compliance with federal, state, and tribal regulatory requirements. [110] This kind of front-end management constrains the practice and evolution of AM and its experiments.

Even though AM has seen obstacles in the Everglades, its practice on a local scale has led to the accomplishment of many strides in ecosystem restoration. This suggests, that if incorporated at a local scale, AM and AG may be beneficial for PV.

Incorporating Adaptive Management and Adaptive Governance in Palo Verde

The incorporation of AM in Costa Rica will face many struggles. However, by looking at systems like the Florida Everglades, Costa Rica can learn from our mistakes and use that knowledge to make the incorporation simpler and more effective. If Costa Rica does this, it may see more benefits from the use of AM than Florida has.

Several steps will streamline the incorporation of AM into the PV wetland. First, legal reform that (1) resolves the conflict between national and international law, and (2) incorporates AM into the law will serve as a basis for AM incorporation. In doing this, legislators should take notice of the restraints Florida has experienced due to a lack of flexibility given to agencies [110] and avoid this. Second, there should be an increase in resources devoted to research and experimentation. AM policies need new experiments, data, and model simulations in order to diminish uncertainties and to adequately recalibrate policies. Third, incremental phases of projects should be used. This will help scientists, policymakers, and stakeholders analyze what aspects of the projects work well and what needs to be improved for the following phases. Fourth, AM should be incorporated at local levels. This will allow for more public participation and may decrease disputes based on differences in agency missions. Finally, Costa Rica's fragmented government may affect AM incorporation in one of two ways: (1) incorporation may be easier because agencies may take a back-seat and let local governments take the lead, or (2) incorporation may be more difficult because of the agencies different missions regarding the same resources. Hopefully these agencies will come together to work with scientists and stakeholders to effectively incorporate AM.

V. CONCLUSIONS AND RECOMMENDATIONS

The Tempisque watershed, in which Palo Verde is located, has been subject to important land-use and water resources changes in the past decades. [111] In 1979, lake Arenal was enlarged to three times its original size for hydroelectric power generation. In the late 1970's, the government of Costa Rica proposed a large-scale irrigation project (Arenal-Tempisque Irrigation Project – PRAT), where water was pumped from the aquifers and the Tempisque river itself, enabling the development of modern intensive irrigated agriculture in this seasonally water-scarce region. [111]

Meanwhile, for conservation purposes, Palo Verde (PVNP) became a National Park in 1980 and cattle grazing in the Park was prohibited. For 250 years, Palo Verde had been a *hacienda*, with up to 15,000 grazing livestock heads [111,112]. Shortly after this and since then, Palo Verde has experienced a spread in native invasive species such as *typha dominguensis* (cattail).

Typha domingensis germinates best with fluctuating temperatures and sunlight and can withstand periods of intense drought as well as flooding [31], making it very resilient to environmental changes relatively to other species. Hybridization between Typha strains adds further complexity to the question of its nativeness and invasiveness in Palo Verde [30]. Management techniques such as the use of fire, grazing, cutting with machete, and the combination of them, have been tried to stop the cattail expansion in PVNP.

Given the uncertainty surrounding the functioning of the wetland and the origin of the ecological changes that occurred at Palo Verde, we suggest an adaptive management approach for PVNP in which any practice management scenarios are previously evaluated through modelling, as is done for classic water management. As a result, cattle trampling influence on soil hydrodynamics should be parameterized in PV's hydrological models. Three main factors should be accounted for in evaluating the effectiveness of cattle trampling on altering soil physical parameters: (1) the initial water content of the wetland's soils; (2) the spatial pattern of cattle grazing; (3) the heterogeneity of the soil's response to compaction.

Costa Rica will face many challenges when incorporating adaptive management into its governance. By learning from other systems where adaptive management has been adopted, Costa Rica can take various steps to simplify the process. The following four steps are recommended: (1) legal reform to resolve conflict between national and international law and to incorporate adaptive management into the law itself, (2) increase in resources devoted to research and experimentation, (3) incremental phases of adaptive management projects, and (4) incorporation at the local level first. If Costa Rica does this, it may avoid may of the problems encountered the Florida Everglades when it first adopted adaptive management and governance.

VI. APPENDIX

INVASIVE CATTAILS (*TYPHA DOMINGUENSIS*) IN PALO VERDE NATIONAL PARK, GUANACASTE, COSTA RICA – Elizabeth Ballare

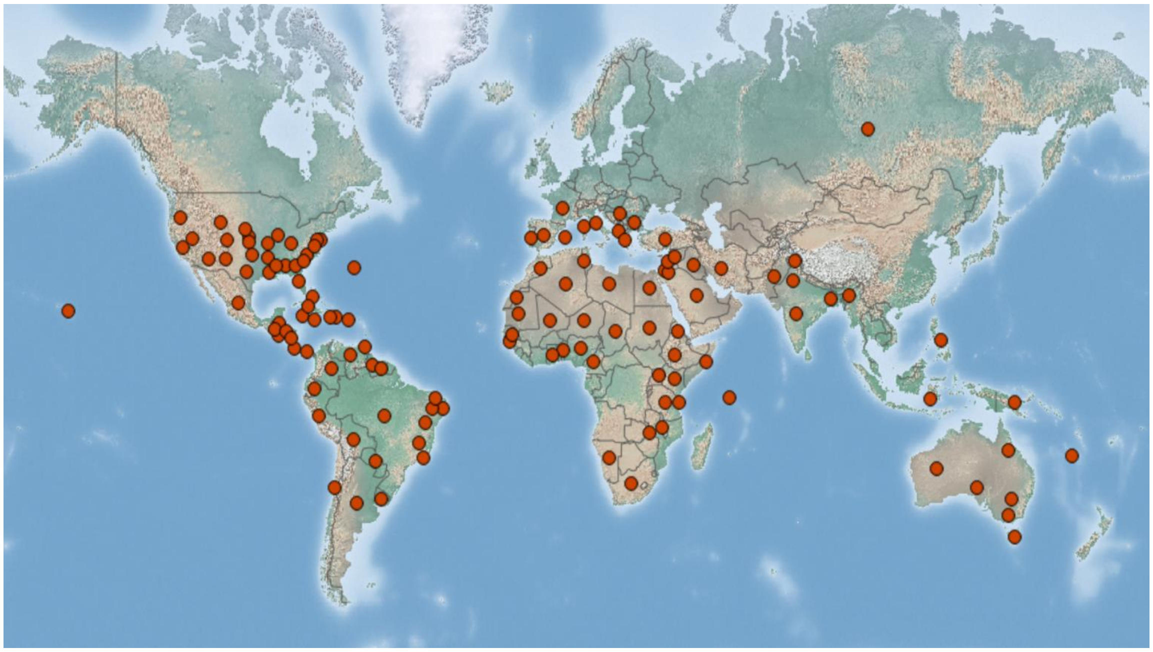

Figure 1. *Worldwide range of Typha domingensis. (Taken from the Invasive Species Compendium).*

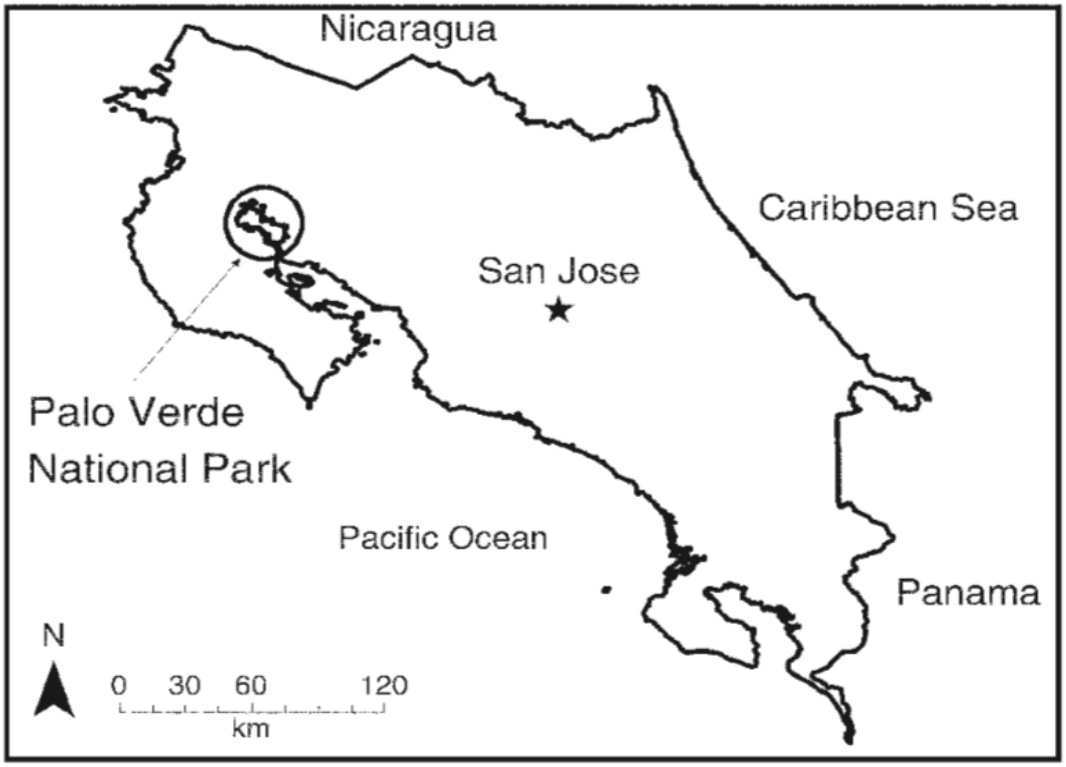

Figure 2. *Location of Palo Verde National Park, Guacanaste Province, Costa Rica. (Taken from Osland et al., 2011).*

WHY PARAMETERIZING MANAGEMENT PRACTICES IN PALO VERDE'S HYDROLOGICAL MODEL? – Pierre Sosnowski

Additional Material for Inquisitive Minds

Modeling Approaches: Lines of Thoughts Drawn from Examples

Taking trampling spatial heterogeneity into account

The way Dunne et al. (2011) [63] took trampling heterogeneity into account was as followed. They first defined the average annual trampling intensity (T_{ave}) as the product of the average annual distance walked by a cattle (D), the average annual stocking density (S), divided by a cow's average stride length (L) multiplied by two (because they have two hoofprints per stride length):

$$T_{ave}\left(\frac{hfpts}{m^2yr}\right) = S\left(\frac{cows}{\cancel{ha}}\frac{\cancel{ha}}{10^4(m^2)}\right)D\left(\frac{\cancel{km}}{(yr)(cow)}\frac{10^3(m)}{\cancel{km}}\right)\frac{2}{L}\left(\frac{hfpts}{m}\right) = \frac{0.2DS}{L}$$

They measured D, L and knew S. In the arid rangelands of Kenya in which the study took place, they considered cattle are regularly herded towards a single watering point such as a borehole from a circle of settlements at a distance R from the well (see fig below). Local trampling intensity T(r) thus rises as distance from the well (r) decreases. Knowing:

$$2\pi rT(r)\mathrm{d}r = 2\pi RT(R)\mathrm{d}r$$

and that the number of hoofprints put down in the catchment of the borehole is

$$T_{ave} * surface = T_{ave} * 4\pi R^2$$

The integration of the footprints as the cows travel from the perimeter of the water source's catchment at 2R to the well (of negligible radius) is (see fig.3)

$$\int_0^{2R} 2\pi r T(r)\mathrm{d}r = T_{ave} * 4\pi R^2.$$

Substituting (2) in (4), then integrating,

$$T(r) = \frac{T_{ave}R}{r}$$

Obtaining an equation giving us trampling intensity as a function of distances, thus allowing spatial heterogeneity to be accounted for.

Relating trampling to infiltration

Following the approach of Dunne et al. (2011) for characterizing trampling heterogeneity, there could be two means for quantifying the effect of trampling on hydrodynamics:

1) By experimentally measuring in the field soil hydraulic conductivity (K) (using double-ring infiltrometers such as in Ferrero (1991)[62]) at different distances (r) from the water source and at different initial water content, allowing for interpolation and extrapolation of measurements;
2) By measuring the effects of the force produced by a hood on the soil under laboratory conditions [64], or based on literature reviewing static pressure applied by hooves of cattle of different size and weight, and quantifying under laboratory conditions the evolution of soil resistance to penetration and BD to different static pressure applied (using Proctor Compaction blows [56,65]) at different moisture content. Then, using hydromechanical modeling approaches like modeling the relationship between soil BD and the soil water retention curve (SWRC)[66], one could take into account trampling-induced BD increase in water transport modeling.

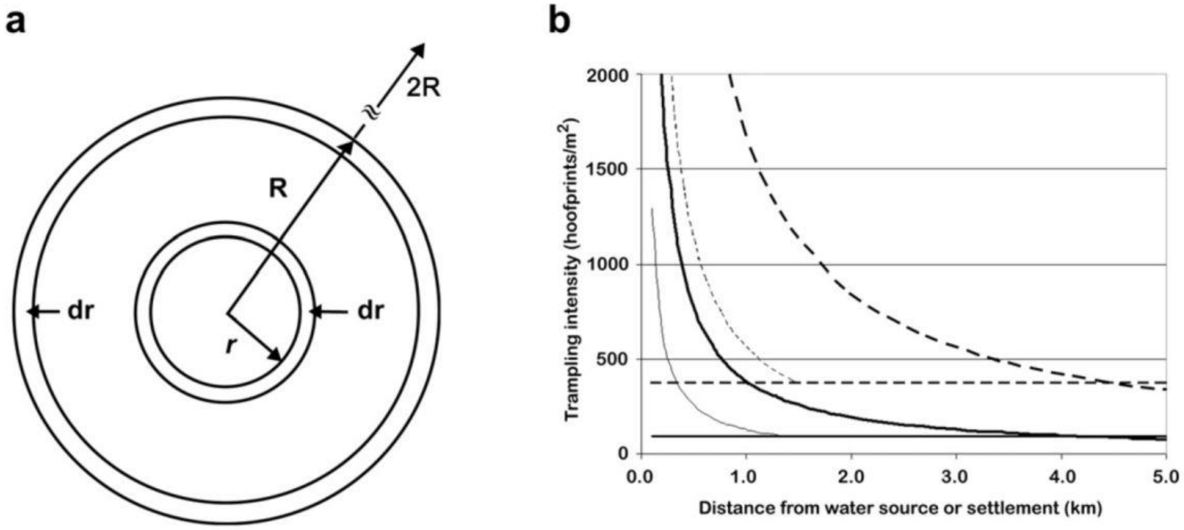

***Figure 3**. Model of the spatial concentration of trampling intensity with distance r around a water source accessed from a ring of settlement at distance R. (a) Schematic diagram; (b) predicted variation of trampling intensity with distance from point and linear water sources at both study sites. The thinner grey curve represents the "background" trampling measured beyond R. From* (Dunne et al., 2011)[63]

Referring to Assouline (2006)[66], Berli et al. (2008a)[67] warn that although his approach is sufficient for many practical applications, bulk approaches lack explanatory power that requires understanding of pore-scale processes to explain vast differences in hydromechanical responses of soils with essential macroscopic porosities and other bulk properties. This could especially be the case in the context of the Palo Verde wetland, where the shrinking-swelling soils already exhibit changes in bulk density with soil water content without any external compressive forces involved.

In their study, Berli et al. (2008a)[67] develop a hydromechanical model for the evolution of aggregate contacts and their impact on interaggregate as well as intra-aggregate fluid flow (see fig. 4). They sought to link the model with the recent (at that time) results from microscale aggregate hydraulics to quantify effects of soil compaction on soil unsaturated hydraulic conductivity. In the context of Palo Verde, where compression is internal (tridimensional isotropic or anisotropic deformation [68,69,70,71] and external (axial load due to trampling[3]), describing the growth of the interaggregate contact between a pair of aggregates due to an axial load and the influence of interaggregate contact area on the unsaturated hydraulic conductivity of the pair of aggregates allows differentiation of the two compressive processes on soil structure and the resulting influence of trampling (axial load) on hydrodynamics.

However, to simulate deformation and hydraulic response of a real pack of soil aggregates, incorporating capillary bridges into their presented model will be necessary. Only then will this hydromechanical modeling approach be upscaled for soil column water flow modeling.

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[3] A force with its resultant passing through the centroid of a particular section and being perpendicular to the plane of the section.

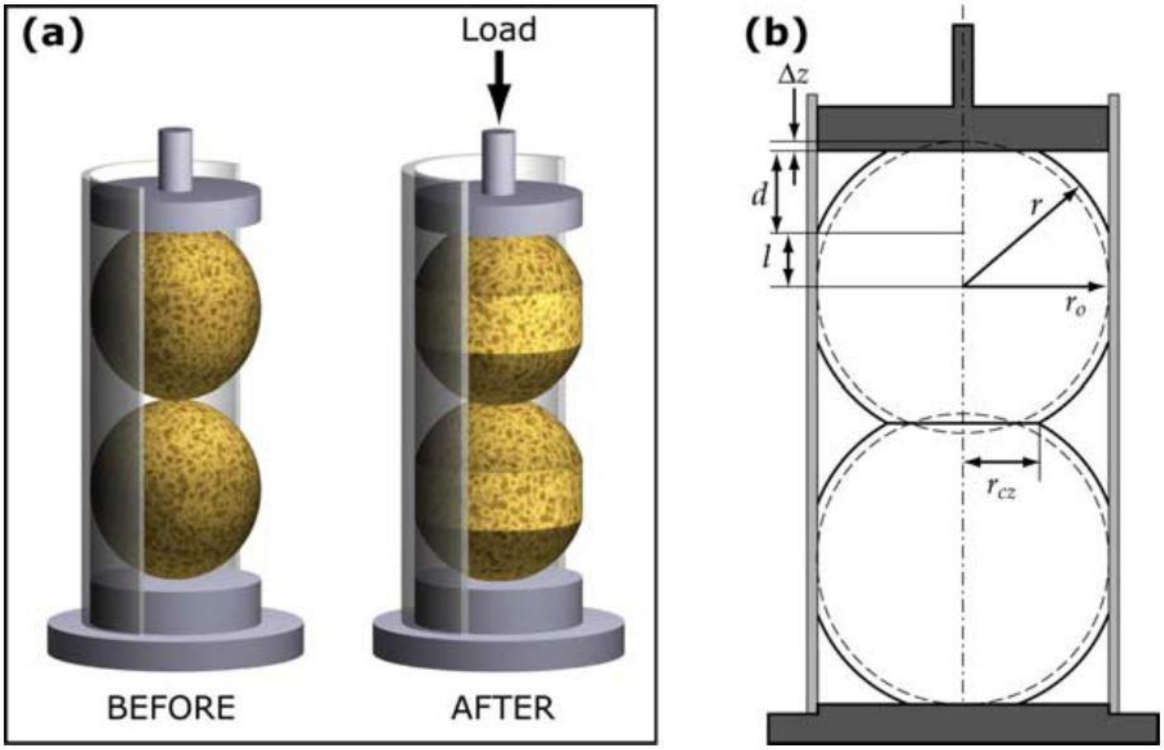

Figure 4. *(a) A pair of uniform spherical soil aggregates before and after undergoing confined, one-dimensional strain and (b) definition of geometric variables. The sample height decreases while the interaggregate contact area increases with increasing strain. From* (Berli, Carminati, Ghezzehei, & Or, 2008a)[67]

Is this the right approach?

This approach is a very Newtonian one[4], meaning the system is modeled based on a physical approach built upon Newtonian mechanics valid at the laboratory or hydrodynamic scale [72] . The beauty (for inductive reductionists at least) is that, as Sivapalan puts it, « *with Newtonian mechanics based models, the role of spatial gradients in controlling hydrologic processes, at least in principle, can be explicitly captured, and so the fidelity of process descriptions at small scales can be guaranteed (at least in principle)* », especially at these times of hyper-resolution modeling. However, there is multiple challenges (or perhaps even limitations) to this approach, as reductionists approach fails at accounting for the functioning of the catchment as an ecosystem, which is defined by (i) processes interactions in the time domain that might be neglected due to the inherently large amount of Aristotelian approximations made when focusing on a large complex system at a microscopic level; (2) the biological/ecological laws defining the exchanges in matter and energy between organisms and its medium (Newtonian theory by itself cannot predict the vegetation and its adaptation strategy at a given place); (3) and finally, despite nowadays immense computing power, hyper-resolution modeling only allows for more accuracy if the heterogeneity of landscape properties are accurately characterized, which is still today one of the major challenge in environmental sciences.

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[4] Also termed *bottom-up reductionist* by (Sivapalan, 2018) [72].

VII. ENDNOTES

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