Review

Use of Remote Sensing to Support Forest and Wetlands Policies in the USA

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Abstract: The use of remote sensing for environmental policy development is now quite common and well-documented, as images from remote sensing platforms are often used to focus attention on emerging environmental issues and spur debate on potential policy solutions. However, its use in policy implementation and evaluation has not been examined in much detail. Here we examine the use of remote sensing to support the implementation and enforcement of policies regarding the conservation of forests and wetlands in the USA. Specifically, we focus on the "Roadless Rule" and "Travel Management Rules" as enforced by the US Department of Agriculture Forest Service on national forests, and the "No Net Loss" policy and Clean Water Act for wetlands on public and private lands, as enforced by the US Environmental Protection Agency and the US Army Corps of Engineers. We discuss several national and regional examples of how remote sensing for forest and wetland conservation has been effectively integrated with policy decisions, along with barriers to further integration. Some of these barriers are financial and technical (such as the lack of data at scales appropriate to policy enforcement), while others are political.

Keywords: environmental policy; remote sensing; forests; wetlands; No Net Loss

1. Introduction

The diversity of technology and infrastructure to monitor environmental systems, from global to local scales, is increasing rapidly as public and private organizations increase their investment in them [1]. These data and images support policy by contributing to new policy development and improvement, as new problems can be discovered or better conveyed to the public visually. Policy implementation and evaluation requires data to ensure compliance and to monitor for policy success. Remote sensing products (including aerial photography, airborne and satellite imagery) are increasingly useful for monitoring and reporting requirements established by national policies and international treaties, conventions and agreements [2].

Remote sensing is used at regional scales to improve land use policy and decision-making, especially for agricultural and urban areas [3,4]. For example, data from AVHRR (Advanced Very High Resolution Radiometer), MODIS (Moderate Resolution Imaging Spectroradiometer) and MISR (Multiangle Imaging Spectroradiometer) satellite sensors have been used to monitor compliance with a biomass burning reduction policy implemented in 2006 in Acre, Brazil [5]. Older aerial photography and Landsat imagery can be used to establish historic baselines for land cover types, and to project the impacts of different policies onto land use trends through alternative futures scenarios [1,6]. Satellite sensors can also warn of excessive air pollution events [7], and aid urban planning by denoting areas in which construction should be modified or banned to reduce flooding and fire damage risks [3]. Satellite platforms that might prove especially useful for the management of urban areas include the fine resolution IKONOS and Quickbird satellites, as well as NASA's Shuttle Radar Topographic Mapping (SRTM) mission [3].

For certain global issues, environmental dynamics may only be understood by appropriately scaled remote sensing data [8,9]. For example, satellite imagery (specifically the Total Ozone Mapping Spectrometer (TOMS) sensors launched on Nimbus and subsequent satellite series) demonstrated the depletion of the ozone layer over polar regions by chlorofluorocarbons, as had been hypothesized [1,7,10]. At present, remote sensing technology is used to track these ozone layer holes on a daily basis, by a partnership between the US National Oceanic and Atmospheric Administration (the Earth System Research Laboratory, Global Monitoring Division) and the National Aeronautics and Space Administration's Laboratory for Atmospheres [11]. This program helps measure the success of the 1981 Montreal Protocol on Substances that Deplete the Ozone Layer, phasing out the production and use of chlorofluorocarbons [12]. The initiation of large-scale programs such as the Global Monitoring for Environment and Security (GMES) for the European Union [2] and the National Ecological Observatory Network (NEON) in the USA also highlight the growing importance of remote sensing and large scale datasets. NEON makes heavy use of remote sensing information, using an Airborne Observation Platform (supporting LiDAR, digital photography and imaging spectrometer sensors) to observe trends in land use change, invasive species, and ecosystem functioning [13].

The Global Earth Observation System of Systems (GEOSS) aims to combine both remote sensing and ground data into one meta-database that could be used to identify risks and evaluate policy success at the global scale [14-16]. GEOSS provides information and tools for nine areas: disasters, health, energy, climate, agriculture, ecosystems, biodiversity, water, and weather [17-19]. The development of GEOSS is driven by the Group on Earth Observations (GEO), an international organization with

members from 85 countries and numerous international organizations [16]. GEOSS is one example of the growing movement to release large datasets to the public, such as NASA's release of all historic LANDSAT imagery and the European Space Agency's intent to make all future satellite imagery free and open access [16].

This review will describe how remote sensing data and technology are being used to implement and evaluate environmental policy. Specifically, we focus on its use for forest management and wetland conservation policies in the USA, as forests and wetlands are often the focus of habitat conservation efforts. We also discuss barriers to its use. Examples of remote sensing in support of environmental policies may be difficult to find in the peer-reviewed literature [1], but are more common in reports generated by national and state-level regulatory agencies. Therefore, much of our descriptions are based on these sources and agency contacts.

2. US Policies Regarding Forests and Wetlands

Policies to minimize the loss of biodiversity and ecosystem services can benefit from the large amount of work being done by hydrologists, ecologists, and other researchers using remote sensing and geographic information systems (GIS). Although the majority of their work is on problem detection and monitoring, agency scientists and staff are using remote sensing and GIS tools to aid their agency's policy enforcement missions. Here we describe those efforts utilizing these tools by the US Department of Agriculture's Forest Service (US Forest Service) to enforce road-related policies, and the efforts of several federal and state agencies and environmental organizations to prevent the loss of wetland area and functionality.

2.1. Roads and Forests in the USA

Undisturbed forests regulate water supplies for many urban and rural areas, support populations of endangered and threatened species, and can prevent the spread of many non-native species. Roads influence the variety and intensity of abiotic and biotic impacts on forested ecosystems at several scales, negatively affecting ecological processes ([20-22], but see [23,24]). The alteration of topography and hydrology involved in road construction often results in increased flooding and erosion, increased desiccation during dry seasons, and increased delivery of sediments and pollutants to aquatic ecosystems [22,25]. Removal of vegetation (particularly trees) along roadsides for safety reasons alters the microclimate of the habitat on either side of the road, providing a pathway for sunlight and higher wind speeds to penetrate forest stands [21]. Generally, wider roads with more traffic and surfaces that are impervious to water have more impacts than smaller and less-trafficked dirt roads, as wider, paved roads typically have more vehicles moving at greater speeds [26]. Greater traffic, paired with drier conditions along roadways relative to forest interiors, also increases the risk of human-set fires, both accidental and intentional [27]. Roads impact biodiversity directly through the loss of habitat (when this habitat is converted to a roadway), but also through the deaths of individual animals in collisions with vehicles. Roads can also fragment animal populations if individuals avoid crossing roads to other habitat patches [21,25]. Plants that require animal pollination may have genetically isolated populations due to the restriction of animal pollinators in this way. Roads also facilitate the spread of invasive species (both plant and animal), by creating disturbed or altered

habitats (reducing competition with native species), and greatly increasing the number of propagules (through "hitchhiking" on vehicle tires, for example; [21,22,28]). The most profound effect of roads is as a catalyst for new impacts into the future; roads facilitate access to remote areas that often beget more road construction and use [29]. Habitat conservation efforts for forested ecosystems often prioritize the minimization of additional roads or widening of existing roads that might further forest fragmentation.

Roads serve as critical social and economic connections between different communities and their natural resources [24]. From the viewpoint of environmental impacts, roads influence up to 20% of the land area of the USA, and 10% of the road length in the US occurs on National Forests [25]. The density of roads in forested areas is higher in the eastern USA than in western forests; core areas of forests without roads averaged 67 ha in the east and 92 ha in the west [20]. One study found that almost no areas within forests were further than 5 km from a road [29], making forests only slightly more roadless than other habitat types. Over 600,000 km of roads exist on US National Forests, the majority of which have been constructed for logging activities [21]. The amount of unofficial or "non-system" roads may represent an additional 97,000 km of roads; these unofficial roads are usually a consequence of off-road-vehicle use [21]. For the past few decades, the US Forest Service has attempted not only to limit new road construction, but also to undergo "road network contraction" [21]. In network contraction, existing roads are blocked, degraded, or even deconstructed along several segments to prevent their use by motorized vehicles, and to improve ecosystem functioning (most commonly to restore streambeds). However, an official road inventory for all national forests has not been completed, and accuracy varies widely amongst management units [24].

2.1.1. Road Policies for the National Forests

Although the US Forest Service has protected forested areas from road building since the 1920s, the 1964 Wilderness Act codified this effort [30]. The Wilderness Act not only set aside 3.7 million ha of Forest Service land into the National Wilderness Preservation System, but also directed both the US Department of Interior and USDA to identify roadless areas larger than 5,000 acres (2,024 ha) within their jurisdiction that could be further considered by Congress to be designated as official Wilderness Areas [31]. Designation as a Wilderness Area prohibits any development, natural resource extraction, or motorized access. The 1976 National Forest Management Act (NFMA) also directs the US Forest Service to identify roadless areas for potential Wilderness Areas, and created a planning process that determines which areas of National Forests should be used for certain purposes (e.g., recreation and natural resource extraction). Unlike the Wilderness Act, the NFMA does not prohibit the establishment of new roads in roadless areas (larger than 5,000 acres).

The concern over the slow pace of Congressional wilderness designation of identified areas prompted the Clinton Administration to issue the "Roadless Area Conservation Rule" or "Roadless Rule". The Roadless Rule came into effect on 13 March 2001 [31]. The rule directs the Forest Service to "establish prohibitions on road construction, road reconstruction, and timber harvesting in inventoried roadless areas on National Forest System lands" [32]. The purpose of this rule was to protect large, uninterrupted tracts of forests (or "inventoried roadless areas") from roads that cause "altering and fragmenting landscapes, resulting in immediate, long-term loss of roadless area values

and characteristics" [32]. These 24 million ha of inventoried roadless areas constitute over one-third of National Forests, about 2% of the land within the USA [31]. The Roadless Rule was supported by the Forest Service, as it provided a political avenue to emphasize its routinely inadequate budget for the construction and maintenance necessary to keep roads in compliance with environmental and safety regulations.

The "Travel Management; Designated Routes and Areas for Motor Vehicle Use" Rule (36 CFR parts 212, 251, 261 and 295), or "Travel Management Rule", is a rule revision to bring the management of national forests into compliance with Executive Orders 11644 ("Use of Off-Road Vehicles on the Public Lands", issued in 1972) and 11989 (an amendment to 11644 issued in 1977). These orders direct all Federal agencies to guarantee that policies regarding off-road vehicles maintain protection of natural resources and ensure the safety of all land users [33]. User-created trails and roads have not been systematically inventoried, although they are estimated to include "tens of thousands of miles" [33]. The new rule was prompted by more powerful and long-range off-road vehicles that became widely available in the past 20 years, and the rapid growth in their popularity and use [34]. The rule identifies the need for a national inventory of all roads and trails, and the creation of a mapping and management system to balance the use of national forests by Off-Road Vehicles (ORVs) with the environmental integrity of the forests, and with other forest uses that may be incompatible with ORVs.

2.1.2. Road Detection in National Forests

Much of the US Forest Service's road identification and mapping efforts are geared towards efficiently targeting surveying efforts (e.g., in areas where the density of unofficial roads are high or increasing rapidly), with the ultimate goal of initiating management efforts to halt the spread of these roads. Each National Forest is responsible for updating its National Forest Land and Resource Management Plan, which provides a map of authorized roads and trails for public use [35]. In the past, few plans were based on thorough inventories of roads and trails. However, with the rapid increase in the use of off-road vehicles in National Forests, the need for comprehensive road inventories was indicated as one of the most pressing threats to National Forests by the Service [35]. Recently, the USDA commissioned a Remote Sensing Steering Committee to identify the most promising remote sensing data and tools for road inventories in National Forests [35]. The committee focused on Dixie National Forest in Utah and Nevada, and Bridger-Teton National Forest in Wyoming, as test cases for a variety of remote sensing and GIS applications.

Werstak *et al.* [35] used 1 m IKONOS satellite images overlaid on GIS maps of "official" roads (the INFRA database) to identify and monitor unofficial roads and trails created by off-road vehicle recreational use in Dixie and Bridger-Teton National Forests. They used two methods (dot grids and grid cells) to estimate road density per 1 acre (0.4 ha) and 5 acre (2.0 ha) grid resolutions. This method was faster and far less labor intensive than delineating individual roads and trails, which in some cases (due to forest cover) was difficult or impossible. Although dot grids missed roads under forest canopy, the method estimated road density which did not require that the entirety of roads was accounted for as uninterrupted linear features. They then used kriging (at a resolution of 2 ha) to identify "hotspots", areas where the density of unofficial trails are highest. In these areas, the density may be so high that

the classification of individual trails is unnecessary; vegetation damage can be so widespread that restoration is required over a large area. Maps of unofficial trail density can then be overlaid with maps regarding natural resources, endangered species habitat, and streams to determine the ecological impact of these trails on each National Forest.

While digital orthophoto quadrangles (DOQ's) were most familiar to forest managers and therefore easiest to interpret, most available DOQ's were up to a decade old, and therefore did a poor job of identifying newly emerging areas of unofficial roads and trails [35]. IKONOS imagery is very useful to identify most roads and trails, and can be used with Feature Analyst to automate road identification to some extent (an iterative process that requires user input between each classification). IKONOS imagery was suitable for identifying unofficial roads, however the resolution was inadequate to distinguish between single and double-track roads; single track indicates mostly non-motorized use (e.g., hiking, horseback riding, and bicycling), while double-track typically indicate motorized vehicles. Airborne digital photographs with a resolution of at least 0.16 m were found to be necessary to make this distinction.

In Ocala National Forest in Florida, Williamson *et al.* [36] found that remote sensing alone was not adequate to create maps of all of the roads and trails. This project illustrated that the resolution of digital aerial photography dramatically influences their effectiveness for identifying roads and trails. The emulsion process for historical aerial photographs also influenced their utility, with natural color providing better information than color infrared; 1:24,000 scale photographs in natural color were most useful. Use of aerial photos (and satellite images [37]) was found to result in many trails and roads being missed under closed forest canopies, substantially reducing the accuracy of the resulting road maps. Substantial ground survey effort (collecting road and trail locations with a GPS) was necessary to create complete maps. In the case of Ocala National Forest, this level of accuracy was necessary to document the impact of off-road vehicle use on sensitive wetlands.

The work completed so far in the test National Forests indicates that fine-grained aerial photography may be necessary in most National Forests to implement the Travel Management Rule. Given the cost of these data, and the staff hours required to collect the ground survey data necessary to verify the classification results, it may be necessary for the US Forest Service to revisit plans to close and decommission major roads that promote the proliferation of ORV trails, and institute other activities that make access to roadless or sensitive areas far more difficult. If the remote sensing is unlikely to ever be sufficient or will remain too costly to support the policies as they stand, perhaps the programs can be altered slightly to meet the potential of staffing levels and remote sensing-based support, at least until the cost-effectiveness of remote sensing data improves.

2.2. Wetland Loss in the USA

The coterminous USA has lost over 50% of the original 90 million ha of wetlands from draining and conversion to other types of land use or land cover [38]. Although earlier in USA history wetlands were primarily drained for agricultural production, more recent losses have been due to filling and development; abandoned and flooded agricultural lands have contributed a substantial portion of the gain in wetland area since 1998 [39]. The Midwestern states have suffered the greatest percentage loss of wetlands on the continent. Gross wetland area losses at the national level, as well as the degradation

of biogeochemical processes and functions of those wetlands, have led to the diminution of specific ecosystem services to the public. These services include: water supply regulation and filtration; protection from flood waters and storm surges; habitat provisioning for terrestrial and aquatic species; and recreational, spiritual, and aesthetic benefits [40].

2.2.1. Wetlands Conservation Policy

The use of remote sensing to assess the loss of wetland area and conditions in the US has paralleled the emergence of the "No Net Loss" (NNL) wetlands target. This target (which has not yet been codified into law) traces its origins back to the National Wetlands Policy Forum (NWPF), convened at the request of the US Environmental Protection Agency Administrator in 1987. The 20-member NWPF developed a policy that was generally intended to "achieve no overall net loss of the nation's remaining wetlands base and to create and restore wetlands, where feasible, to increase the quantity and quality of the nation's wetland resource base" [41]. The NNL policy goal was to stop the decline in overall wetland area loss throughout the USA. However, the NNL does not specifically refer to the ecological functions, services, or values of wetlands that are lost through destruction or degradation, or gained through restoration or creation. Since the establishment of the NNL, several US administrations have added the additional goal of reversing wetland losses through wetland creation and restoration, not merely stopping the loss. Importantly, the goals of the NNL policy do not address the comparability of wetlands that are created, restored, or destroyed, placing the emphasis on the area of the wetlands as the sole determinant of NNL policy success, exclusive of all other wetland conditions.

Shortly after the formalization of the NNL policy, in a 1990 Memorandum of Agreement between the US Army Corps of Engineers (ACoE) and the US Environmental Protection Agency (USEPA), both committed to mitigate for unavoidable wetland impacts and to offset environmental losses from those impacts that were unavoidable. The purpose of the Memorandum was to demonstrate compliance with Clean Water Act (CWA) Section 404(b) (1) guidelines that regulate the dredging or filling of wetlands [33 USC. 1344(b)]. Such mitigation was agreed to also provide for the functional replacement of wetlands that were lost in the landscape, referred to as "no net loss of values". The Memorandum specifies a minimum area replacement ratio of 1:1 or greater if the replacement wetlands are of lower "functional value or (if) the likelihood of success of the mitigation project is low." Conversely, the wetland area replacement ratio may be less than 1:1 if the affected wetland functions and values are low or the likelihood of success of the proposed wetland mitigation is high.

The linkages between the NNL policy and Section 404 of the CWA established policies, procedures, and programs that regulate the dredging or filling of wetlands, as well as any loss of wetlands area and some wetland functions (e.g., biogeochemical processes within the wetlands), and services/value(s) associated with those wetlands (*i.e.*, those wetland functions that have human utility). Section 404 of the CWA and/or the NNL policy comes into play whenever an activity (usually attributed to intentional development) results in the filling or loss of wetlands. Some activity exemptions are granted for certain farming and forestry activities. Since proposed major activities are regulated through a permit review process, the US ACoE, the USEPA, relevant State agencies, and the US Fish and Wildlife Service (USFWS) are usually involved. Each of the parties involved utilize a number of techniques to inform decision making and policy determinations *vis-à-vis* the CWA and the

NNL policy. These techniques frequently involve remote sensing data interpretation by regulatory decision makers and their technical or research colleagues/staff. Since the early 1970s, the sole use of hard-copy photography has been supplemented with both printed and digitally stored photographic images, along with a myriad of other digital sensor data, with detailed accounts of these uses provided in the following sections.

2.2.2. Remote Sensing and Wetlands at the National Scale

Remote sensing data have been used extensively to assess both the loss of wetland area and, to a lesser degree, to assess the loss of wetland functions and services in the USA. These efforts have led to a more detailed understanding of wetland conditions, such as vegetation community characteristics, hydrologic regimes, and soil conditions. These biophysical details can identify degradation that affects the total functional area of a wetland, as well as the ecosystem services it may provide. However, these efforts have rarely led to anything beyond limited requirements for monitoring.

The USFWS is required by the Emergency Wetland Resources Act of 1986 to provide Congress with a status and trends report for all of the nation's wetlands [16 USC 3931 (a)], which was to begin in 1990 and continue thereafter. Photogrametric techniques are utilized extensively to focus attention on the nationwide policy goals and policies to assess wetland area loss and the fundamental characteristics of those wetlands, coordinated by the USFWS. The survey currently combines color infrared IKONOS and aerial imagery with field data collected at a stratified random sample of plots to estimate wetland gains and losses for over a dozen wetland types. However, these assessments are made every ten years, which may limit the time-sensitive needs of policy makers. The first report (for the coterminous USA) estimated the annual rate of wetland loss at 185,346 ha from the mid-1950s to the mid-1970s [42]. Subsequently, a national decline in the rate of wetland loss was reported by Dahl and Johnson [43], finding that from the mid-1970s to the mid-1980s wetland losses were approximately 117,360 ha per year. Dahl [44] provided additional evidence that wetlands losses further declined between 1986 and 1997, at a loss rate of 23,680 ha per year, an eighty percent reduction in the overall average annual rate of wetland loss compared with the previous decade. The most recent assessment of the USFWS occurred for the period of 1998 to 2004, during which time there was an approximate net gain of 77,600 wetland ha nationwide, which Dahl [39] equated to an average annual net gain of 12,950 ha for the coterminous USA.

The USFWS used similar photogrammetric techniques to recently assess total area of wetlands in Alaska, totaling over 70,692,000 ha, which is 43.3 percent of Alaska's total surface area and 5.2 percent of the total surface area of the coterminous USA. Deepwater habitats (such as lakes, bays, sounds, fjords, lagoons, and inlets) in Alaska occupy an additional 12,088,200 ha, or 7.4 percent of Alaska's total surface area [45]. Since the 17th Century, one-tenth of one-percent of Alaska's wetlands have been lost. Although total wetland losses in Alaska are relatively small as a total proportion of all wetland area, specific localities in Alaska have experienced substantial losses [46].

The stated NNL policy goals and regulatory policies and procedures articulated by Section 404 of the CWA offer clear and unambiguous guidance for those parties that are measuring the loss of wetland area, functions, and values. It is important to recognize that neither the NNL policy nor the CWA specifically mandate conserving or restoring the wetland ecological functions and (to an

increasing degree) ecosystem services that have been the focus of remote sensing research in wetlands, even though these topics are emerging priorities for a number of regulatory and resource agencies. These priorities are either explicit, such as the US Forest Service's Section 2709, Food, Conservation, and Energy Act 2008, or implicit by their programmatic emphasis on ecosystem services in wetlands, such as USEPA's Ecosystem Services Research Program focus on wetlands [47] and the USACoE's focus on ecosystem service-oriented restoration [48]. However, the primary use of remote sensing has been the assessment of area losses, with limited application to detail regarding the biotic and abiotic characteristics of those wetlands, except for some regional assessments of wetland functions and their losses (e.g., 54, 93). (Here, characteristics of wetlands include the presence of hydric soils, average hydrologic regime conditions, and coarse level vegetation types [38,39,42-45].) Attention to assessing wetland ecosystem services and values (particularly at the regional or national levels) is almost non-existent.

2.2.3. Regional-Scale Wetlands Programs Using Remote Sensing

A substantial number of wetland functional assessments have been conducted using a combination of field-based measurements (e.g., soil, water, hydrologic regime, and biological data) and airborne or satellite based remote sensing data at the local and sub-region scale, providing information about wetland ecological functions, some of which are also ecosystem services. Much of this research information utilizes multispectral scanners, such as Landsat, Satellite Pour l'Observation de la Terre (SPOT), and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and is focused on issues such as wetland change [49-53] and vegetational stress [54].

Regional Use of the National Wetlands Inventory

The Emergency Wetland Resources Act of 1986 prompted the creation of the National Wetland Inventory (NWI) program, which provides for a series of data and maps, complementing status and trends reports (described in Section 2.2.2) for all of the nation's wetlands. The NWI uses relatively fine resolution aerial photographic imagery (scales typically ranging from 1:58,000 to 1:80,000) to generate maps and statistical analyses for the public. The maps provide trends in wetland area, as well as information about the hydrologic regime of mapped wetlands, presence of hydric soils, and general types of wetland (e.g., herbaceous, scrub/shrub, or woody) vegetation [55]. NWI assessments and associated trends analyses are used by multiple Federal and State agencies, the scientific community, the private sector, and conservation groups for decisions that relate to development, and landscape change, to help formulate and evaluate wetland policies. Despite their potential usefulness for jurisdictional wetland decision making, the NWI Program explicitly states that their data are not intended for regulatory purposes and so Federal, State, or local regulatory agencies must utilize the NWI solely as a guide, often along with additional field-based information to provide any legal determinations about wetlands (such as their legal boundaries). In addition to the direct application of the NWI Program's remote sensing data and analyses to national wetland NNL and CWA policies and procedures, many regional programs utilize the data for specific wetland policy goals and decisions.

A number of efforts are ongoing to modify and update the NWI, primarily using additional aerial photography from overflights to address specific regional policy interests that require updates on

wetland change. As regional modifications to the NWI are such a tremendous undertaking, consortia of State, private, non-governmental, and federal organizations typically conduct them. For example, the Great Lakes/Atlantic Regional Office of Ducks Unlimited (DU) and the USFWS are leading the update of the NWI for the Great Lakes and Northeastern states, with major updates currently completed or in progress in Michigan, Ohio, Indiana, and Illinois [56]. The updates utilize 2000's photography to revise the original NWI so that the region's inventory of wetlands is more current and accurate. DU utilizes the wetlands mapping updates to advocate for the conservation of wetlands and waterfowl habitat to Congress and State governmental agencies.

The NWI has been used as a base map for the Chesapeake Bay watershed [57], which is an important resource for the eastern seaboard with its many coastal and inland wetlands. Working with academic and interest group researchers, the USEPA has used airborne hyperspectral data to map submerged aquatic vegetation (SAV), allowing for the development of semi-automated techniques in the tidal Potomac River [58]. Landsat multispectral scanner and thematic mapper data have also been utilized to map certain SAV plant communities [49] in the Chesapeake Bay region. SAV plant communities provide critical food, shelter, and breeding areas for waterfowl, fish, shellfish, and other aquatic life, which in turn provide tremendous commercial value to the public that live in, or otherwise depend upon, the Chesapeake Bay. Policy linkages to remote sensing use is key to the Chesapeake Bay Program's monitoring of long-term changes of chlorophyll-a in tributaries and the bay-estuary ecosystem, informing the Program's (and regional partner's) assessment of, and plans to combat, nutrient over-enrichment of the Bay [59]. Other coastal US resource policy planning groups (e.g., The Rhode Island Coastal Resources Management Council [60]) actively utilize remote sensing data and methodologies to make policy decisions influencing wetland and deepwater habitat conditions in the Narragansett Bay Watershed, with the use of remote sensing derived data in a GIS, such as the Habitat Priority Planner (HPP). The HPP provides decision makers with wetland and other ecosystem data for conservation, restoration, and land use planning in an understandable scenario-building environment, allowing decision makers to visualize potential land use policy impacts upon wetlands and other ecosystems that affect the quality of the coastal zone environment [61].

The Chesapeake Bay and Narragansett Bay Programs are representative uses of remote sensing data for the purposes of regional and local level planning and decision making. These policy decisions use current data about wetland resources, in addition to relatively fine-grain information (e.g., details of the boundaries of the wetland vegetation, and current location or condition of wetland vegetation species). These programs require remote sensing data that are more current or collected more frequently (*i.e.*, multiple consecutive years and/or seasons) than the NWI can provide. For specific local or regional issues, decision makers often seek additional remote sensing data at a temporal scale and temporal frequency that is relevant to their needs (*i.e.*, timely and relevant budgeting of development programs, implementation plans, or public outreach activities). For example, in the Chesapeake Bay Program, the use of hyperspectral airborne data could be used to provide the necessary SAV species information because of the relatively narrow bandwidth characteristics of low altitude airborne hyperspectral scanners (e.g., HyMAP, CASI, or AVIRIS). The use of hyperspectral scanner data could also provide relatively fine-grain delineation of wetland size and shape, compared to the relatively coarser spatial and spectral characteristics of Landsat data currently utilized in the Program [59]. Conversely, Landsat data may provide a broader "landscape assessment" of SAV

communities across a relatively vast area (e.g., the entire Bay), but without distinguishing each SAV species.

3. Implementation Barriers

As the forest and wetland conservation examples demonstrate, remote sensing data and technology are currently being used to implement and enforce policy. Below we describe current efforts in Brazil and the Prairie Pothole Region of the USA to suggest the extent to which remote sensing use can be automated to prioritize areas to protect (or restore) to help achieve policy goals. These efforts suggest that federal and state agencies are not using remote sensing for policy support to the extent that they could to achieve their respective agency missions. There may be substantial barriers to overcome before the application of remote sensing to policy implementation and evaluation becomes widespread and automatic.

3.1. Emerging Opportunities for Policy Applications

The US Forest Service could more easily meet its responsibilities to identify roadless areas for protection and generate up-to-date road network maps for the public by increasing the application of remote sensing data and technology. Semi-automated or automated software for road detection and road network monitoring from remote sensing data could be used to meet these responsibilities faster and with fewer staff [62], although many of these efforts have focused on urban areas (e.g., [63,64]). Remote sensing has been extensively used in other countries to first visualize and then track deforestation, particularly after road construction [20,65,66]. Indeed, one of the most striking examples of the self-perpetuating impact (where disturbance begets more disturbance) of "unofficial" and official roads was the "fishbone" pattern of forest clearing in the Amazon rainforest [67] (Figure 1). Similar to ORV-created roads in National Forests in the US, the impact of "unofficial" (*i.e.*, illegal) roads may be greater than official roads [68,69]. Brazil's National Institute for Space Research (INPE) hosts a website with Landsat images and software ("SPRING") which allows researchers to quickly identify areas of the Amazon where high rates of "unofficial" (*i.e.*, illegal) roads are encroaching on pristine forest areas, so that these areas can be officially protected [70,71].

Policies developed more recently may be more likely to use remote sensing for implementation and enforcement, as the technology has become more familiar to decision makers. Proposals for global climate change policies to be implemented at the national scale are emerging as the active phase of the Kyoto Protocol come to a close. At present, about 20% of global greenhouse gas emissions have been traced to deforestation and degradation of tropical forests [73]. Deforestation and degradation must be quantitatively linked to carbon emissions (later policies may add carbon sequestration due to land use change into national evaluations of emissions). In particular, the policy development phase for the Reducing Emissions from Deforestation and Degradation (REDD) programs under the Kyoto Protocol has explicitly incorporated discussions on the strengths and limitations of remote sensing data to help with policy monitoring and compliance [74]. The REDD program may be one of the most advanced examples of the systematic use of remote sensing in all phases of the policy cycle, including evaluation and regulation [73,75]. The Global Forest Observation Initiative will use remote sensing to support a global accounting system for forest carbon sequestration and releases for the REDD program [16]. The

Landsat satellite series has the historical breadth and appropriate resolution to provide historic national-scale baselines for forest cover back into the 1970s [69]; the baseline is critical for REDD accounting. The search engine giant Google is working with scientists to allow them to utilize the company's computational resources to analyze large amounts of satellite imagery to quickly identify new areas of deforestation and calculate the rate of forest loss, with the intent to support policies such as REDD [76].

Figure 1. "Fishbone" pattern of deforestation off of a main road in Amazon forest in Rondônia, Brazil **(a)** in 1975 prior to main road construction (Landsat 2 MSS), **(b)** in 1986 just after the main road was built (Landsat 5 MSS), and **(c)** in 1992 (Landsat 4 TM) [72]. Red color indicates vegetation, light blue is bare ground. Images from US Geological Survey [72].

(a)   **(b)**

(c)
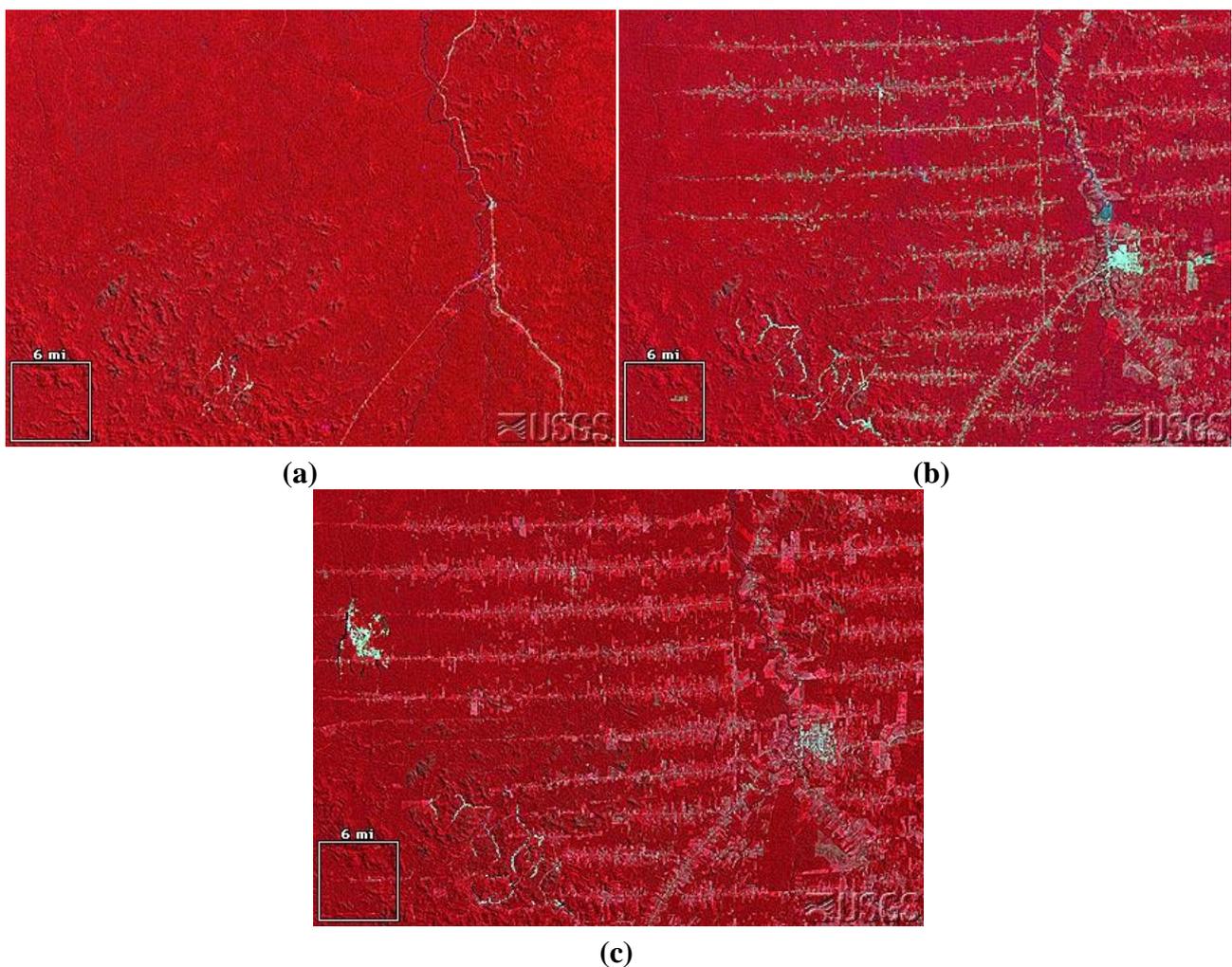
On the other hand, advancements in remote sensing applications seem to far outpace their use for policy support, even when the opportunity to do so is apparent. The US portion of the Prairie Pothole Region (PPR) of the Upper Midwest (Montana, North Dakota, South Dakota, Iowa, and Minnesota) has been studied in detail using remote sensing. A result of glacial activity, the PPR landscape is characterized by both temporarily and permanently inundated "potholes" containing a variety of submerged, floating, and emergent vegetation that is critical habitat for waterfowl and other species.

Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) have been used to map potholes every 16 days, allowing for within and/or between-year investigation of changes in water surface extent [77-79]. Due to its resolution, Landsat TM data can miss potholes smaller than approximately 0.9 ha (which may make up the majority of wetlands in the PPR) [77], so researchers have used subpixel classification techniques that allow for identifying wetland targets smaller than the sensor's field of view [53,78]. Winter and Rosenberry [79] used the subpixel classification techniques with TM and ETM+ data with some success to inventory open water and lakes in the vicinity of Devils Lake (North Dakota) of the PPR from 1991 to 2002, over a wide range of climatic conditions, making the technology very applicable to the region's wetland monitoring needs.

Although remote sensing methods have been extensively used to monitor changes in the surface water extent of potholes and other terminal lakes (e.g., [80-82]), few of the results have been used to support specific environmental policies, regulatory actions, or for setting/measuring conservation program goals. The lack of policy linkages to the ongoing research is particularly unfortunate because the remote sensing techniques in the PPR are very reproducible (with great potential for use in other depressional wetlands) and require relatively simple analytical techniques, such as traditional classification and density slice approaches (e.g., [83-86]). This lack of coordination has profound implications for wetland related ecosystem functions; the PPR is home to more than 50% of North American migratory waterfowl, and provides critical wetland ecosystem services such as reduction of downstream flooding, hunting opportunities, and birding/recreation. Some of these species are protected by the Migratory Bird Treaty Act of 1918. Without the application of remote sensing to policy decision making, the PPR may continue to lose wetland area and ecological functions; the PPR has already lost more than 50% of its wetlands, including their attendant ecological functions, to land conversion and other activities [87].

3.2. Barriers to Use for Environmental Policy

One of the important outcomes of remote sensing over the past 40 years is the ever-widening array of derived geospatial data sets that have been produced, such as topographic data, stream networks, soils data, watershed boundaries, land cover data, and climate data, to name just a few. Consequently, remote sensing-based geospatial datasets are now available to local, regional, and national policy makers and their technical staff. In addition, environmental scientists of many specialties have used the geospatial data to calculate a wide variety of landscape metrics and models, particularly related to the assessment of stream, river, lake, and wetland condition (e.g., [88-94]). Additionally, user friendly software tools have been developed and made available to decision makers, such as the Analytical Tools Interface for Landscape Assessments [95]. This software is an ArcView (ESRI Inc.) extension, and provides one of many ecosystem screening tools that can calculate landscape conditions within wetlands and adjacent to wetlands, as well as other ecosystem types.

Despite these technological developments, the use of remote sensing for implementation and evaluation of environmental policies remains low. While it is not possible to determine the exact barriers for use to support a particular policy without in-depth investigation, some of the more likely reasons may include cost and inappropriate scale of the data, and lack of policy prioritization to justify the expense (in time, resources, and staff).

Cost of Products: The demand for these technologies must be sufficiently high to offset their cost [1]; this may explain why some areas of environmental policy make more regular use of these technologies than others. While Landsat images (at 30 m resolution and ~675,000 ha extent) are currently available for free, data requirements at finer resolutions might require aerial photographs (with costs dependent upon both the cost of the camera or sensor equipment as well as costs of air time) or fine-scale satellite imagery; these can run over $1,500 for an IKONOS image (at 1 m resolution and ~16,500 ha extent), for example. Licenses for basic, popular GIS software packages can thousands of US dollars per year per seat, and require computers with multiple, high-speed processors to run them. In industrialized countries, ground-level surveys and data collection programs for small areas (perhaps comparable to an IKONOS image extent), when loaded into Geographic Information Systems, may provide the same types of information as those available from remote sensing, but with greater accuracy and at lower cost [3]. As the monitoring area increases, the economic efficiency of remote sensing approaches will meet (and over very large areas exceed) a monitoring program based on ground surveys.

Inadequate Resources for Staff or Training: At the local and regional scales, government agencies may not have the personnel, training, or resources to make use of available data [96]. An explicit cooperation between remote sensing scientists, GIS analysts, and policymakers could overcome some of the political barriers (e.g., the "science-policy value gap") related to training, experience, and resources [7]. This can include programs which place policymakers from regulatory agencies in agencies charged with delivering and interpreting remote sensing information [7]. The use of automated or semi-automated software that can quickly update road networks [62] could help alleviate a staffing shortage, although whether these automated programs could effectively deal with irregularly sized trails (commonly created by ORVs, bicycles, and horses) running under evergreen forest canopies remains to be seen. Approaches using neural-network-based models to detect cross-border smuggling trails may be more appropriate [97].

Data at Appropriate Scales not Available/Affordable: Barriers to the use of remote sensing data and technology may also form due to characteristics of the data (such as accuracy, consistency, and timeliness) [1], and whether the data are available at scales relevant to the policy's jurisdiction and focus. Limited use of remote sensing data for policy decisions in the past has been related to the relatively coarse resolution of certain satellite data (e.g., Landsat, AVHRR, and MODIS), and the prohibitively high cost of acquiring and processing more specialized, higher spatial or spectral resolution data (e.g., hyperspectral or LiDAR), as well as the relatively specialized training/staff required to process these data.

For example, regardless of its resolution, remote sensing imagery may not detect small roads running under forest canopy, although pairing these data with up-to-date road maps and GPS field data can overcome this shortcoming [36,37]. The use of coarse-scale images can cause many smaller (but still important) roads to be missed. Working on forest fragmentation, Heilman *et al.* [20] found that the length of detectable roads increased by 40% when switching from 1:100,000 scale to 1:24,000 scale data. The utility of these products may increase if they are developed in response to requests from potential users and a systematic survey of needs of existing policies and programs, instead of developing the products first and making them available to users afterwards [2]. This type of survey

also helps to illuminate where the same basic remote sensing product can be used to meet multiple programmatic objectives of several different agencies or institutions, reducing the costs across all agencies [2].

There are many examples of regional, state, and local remote sensing programs for monitoring and assessing wetland conditions (such as those described above) that use a variety of high resolution and low resolution airborne and spaceborne remote sensing data. Yet specific local, regional, or national coordination between wetland remote sensing and policy activities are still quite rare. Rivero *et al.* [98] demonstrated a very specific application of Landsat ETM+ and ASTER for mapping the spatial variability of vegetational detritus and soil total phosphorus, using remote sensing to infer soil nutrient status in the large wetlands of the Everglades. However, specific research applications of remote sensing results such as these are not routinely incorporated into policy, and in this case could be very valuable for guiding Everglades policy, plans, and programs, specifically the Florida Department of Environmental Protection's Comprehensive Everglades Restoration Program [99] and the Northern Everglades and Estuaries Protection Program [100]. Both of these programs have identified anthropogenic nutrient influx as a top priority for restoring the Everglades' structure, function, and resilience.

Political Reasons: There can be non-technical reasons why some policies may be difficult to support in general, irrespective of technologies available for enforcement. The Roadless Rule has been a politically contentious policy from the start, with numerous lawsuits that have challenged its legality for over a decade [30]. Given a history of limited budgets within the Forest Service, dedicating staff and resources to the development of remote sensing-based support of the rule may be difficult to justify, even if technically straightforward. The "No Net Loss" goal has not been officially codified into law by either the Executive nor Legislative Branches, and instead must be inferred as the "spirit" of laws such as President Carter's 1977 "Protection of Wetlands" Executive Order 11990 and the Clean Water Act. The USA is a signatory to two international laws (the Migratory Bird Treaty Act [101] and the Ramsar Convention on Wetlands of International Importance [102]) that do call for a halt to wetlands destruction and degradation, but the practical commitment of the US Federal Government to meeting these agreements may fluctuate with political circumstances. Indeed, the use of remote sensing to track Prairie Potholes and other small or ephemeral wetlands would seem to be an obvious approach for the US government to demonstrate that these treaties are being upheld.

Scientists could help decrease the impact of staffing and data resources shortages by communicating and working more closely with policy developers and implementers. While much of the theoretical research in remote sensing has demonstrated how these technologies and data might be used, this research could be better designed to achieve both theoretical and applied objectives. When scientists develop hypotheses, choose study areas, or purchase or request remote sensing imagery, communications with local and regional regulatory agencies could increase the utility of the research to help prioritize the agency's ground survey efforts or changes to law enforcement. Indeed, using policy goals as an endpoint and quantifying the distance between current and desired conditions using experimental remote sensing techniques is an important but severely underused approach to hypothesis testing. For example, given that all National Forests must identify roads and roadless areas in order to generate travel management plans, researchers developing new methods to map narrow trails in

heavily forested areas from fine-grained imagery could use National Forests as their study areas, and use the ground survey performed by US Forest Service personnel for accuracy assessment. In this way, the research gains an independent dataset for verification of the approach, and the US Forest Service gains a remote sensing analysis of their area without the cost of imagery and the GIS technical staff to analyze it. Alternatively, as stated in Section 2.1.2., it may be equally prudent to alter policies and programs to allow for adequate remote sensing support, although it may be a compromise that is just as politically difficult to defend as increased expenditures on remote sensing technology and data to support existing policies.

4. Conclusions

Four decades of remote sensing data from several series of global orbiting satellites offer ample opportunities to establish baselines for many environmental problems [1]. Habitat conservation would seem to be a perfect candidate for the widespread use of remote sensing data and automated technologies to ensure that conservation laws are being successfully implemented. However, the degree to which these technologies are being used falls far short of their potential, with a variety of technical, financial, and political reasons likely the cause of the shortfall.

Reid *et al.* [9] issued a call to explicitly link research on global environmental change with sustainable development. This would encompass the use of remote sensing for not only monitoring environmental conditions, but measuring the feedbacks between these conditions and human activity and governance. Remote sensing data could be incorporated into large, complex models of socioeconomic systems (to help determine the social and economic impacts of environmental changes), and existing efforts (such as GEOSS) could be modified to include an assurance that its products would meet the needs of decision-makers and are scaled appropriately for sustainable development policy.

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