Gulf-wide data synthesis for restoration planning: Utility and limitations

By

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ABSTRACT

Multiple funding mechanisms support restoration across the northern Gulf of Mexico. To maximize environmental, societal, and financial benefits of these investments, best use of available science is needed to inform project prioritization and planning processes. Synthesizing available data across the northern Gulf of Mexico can provide information on potential threats to, and benefits from, projects or suites of projects. To achieve this, subject matter experts from Alabama, Florida, Louisiana, Mississippi and Texas were identified with recommendations from each of the RESTORE Act Centers of Excellence. These experts provided known sources of Gulf-wide data and recommended metrics that would be most informative, resulting in 40 threat, 19 habitat and 10 community primary data layers. Two tessellated geospatial hexagon grids were generated to provide uniform coverage that encompassed a 25-mile buffer of the Coastal Zone Management Act (CZMA) boundary at a spatial grid resolution of 100 km^2 and 1 km^2. The two resultant grid domains included all counties in the five Gulf states determined by the National Oceanic and Atmospheric Administration (NOAA) as contributing to coastal watersheds. The varying grid resolutions allowed for data to be spatially visualized both at a broad Gulf-wide scale on the 100 km^2 grid as well as at a regional and project level scale on the 1 km^2 grid. The data layers were synthesized into combined layers of potential stress, potential ecological benefits, and potential community benefits. These layers support broad scale prioritization for restoration efforts, based on likelihood of success and desired outcomes. The synthesized data were discussed in the context of the five goals and four priority criteria of the Gulf Coast Ecosystem Restoration Council's (RESTORE Council) aim of using best available science (BAS) to guide future funding for restoration at large and small scales.

KEYWORDS: Stressors, ecosystem services, human well-being, coastal restoration, land conservation, RESTORE Act, RESTORE Council, Deepwater Horizon, DWH, Natural Resource Damage Assessment, NRDA.

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There are multiple large funding and programmatic mechanisms to support restoration in the northern Gulf of Mexico. Since the Deepwater Horizon (DWH) oil spill in 2010 and the subsequent settlement, restoration efforts have greatly increased and will continue to do so over the next 15 years. To maximize environmental, societal, and financial benefits of this investment, it is essential to ensure best use of available science to inform prioritization and planning processes. Extensive research and monitoring have occurred across the northern Gulf of Mexico. However, these activities have largely addressed individual questions, not focused on standardized metrics, been separated by governance boundaries (e.g. between states) or across agencies (federal and state) and been collected at a wide variety of spatial and temporal scales.

Returning a restored area to the condition of an undisturbed site is widely recognized as unrealistic given that ecosystems are highly dynamic and do not tend towards stable states (Wyant *et al.* 1995). Desirable restoration outcomes should be defined through identification of ecological and social functions and services that work towards a self-sustaining (if dynamic) ecosystem. These benefits often necessitate tradeoffs and therefore require management goals and community engagement to prioritize relative benefits (Wyant *et al.* 1995). Motivations for restoration are diverse, including habitat protection, biodiversity enhancement, and ecosystem service provision such as improved water quality for consumption or recreation. Alignment of the motivations for restoration with planning and monitoring improves prioritization of projects and establishment of realistic expectations amongst stakeholders and implementing mechanisms (Hagger *et al.* 2017).

The largest current mechanisms for funding coastal restoration along the northern Gulf of Mexico result from the DWH oil spill and subsequent settlements. The Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States (RESTORE) Act established a new trust fund in the Treasury of the United States, known as the Gulf Coast Restoration Trust Fund (from https://www.treasury.gov), and created the RESTORE Council as an independent federal entity. Portions of funding overseen by the RESTORE Council are guided by four priority criteria and five Comprehensive Plan goals (U.S. Congress 2012; Gulf Coast Ecosystem Restoration Council 2016) (Figure 1A, B). These goals and criteria are a critical guide to the data compilation and spatial mapping effort described herein.

Monitoring restoration effectiveness continues to be a challenging undertaking. Ecosystem benefits, functions, and services are partially integrated into the planning and decision-making process of ecosystem conservation and restoration projects. These blind spots can be in part attributed to the absence of a defined methodology capable of integrating applicable geospatial data at a scale and resolution suitable to drive informed decision making. A data-driven framework

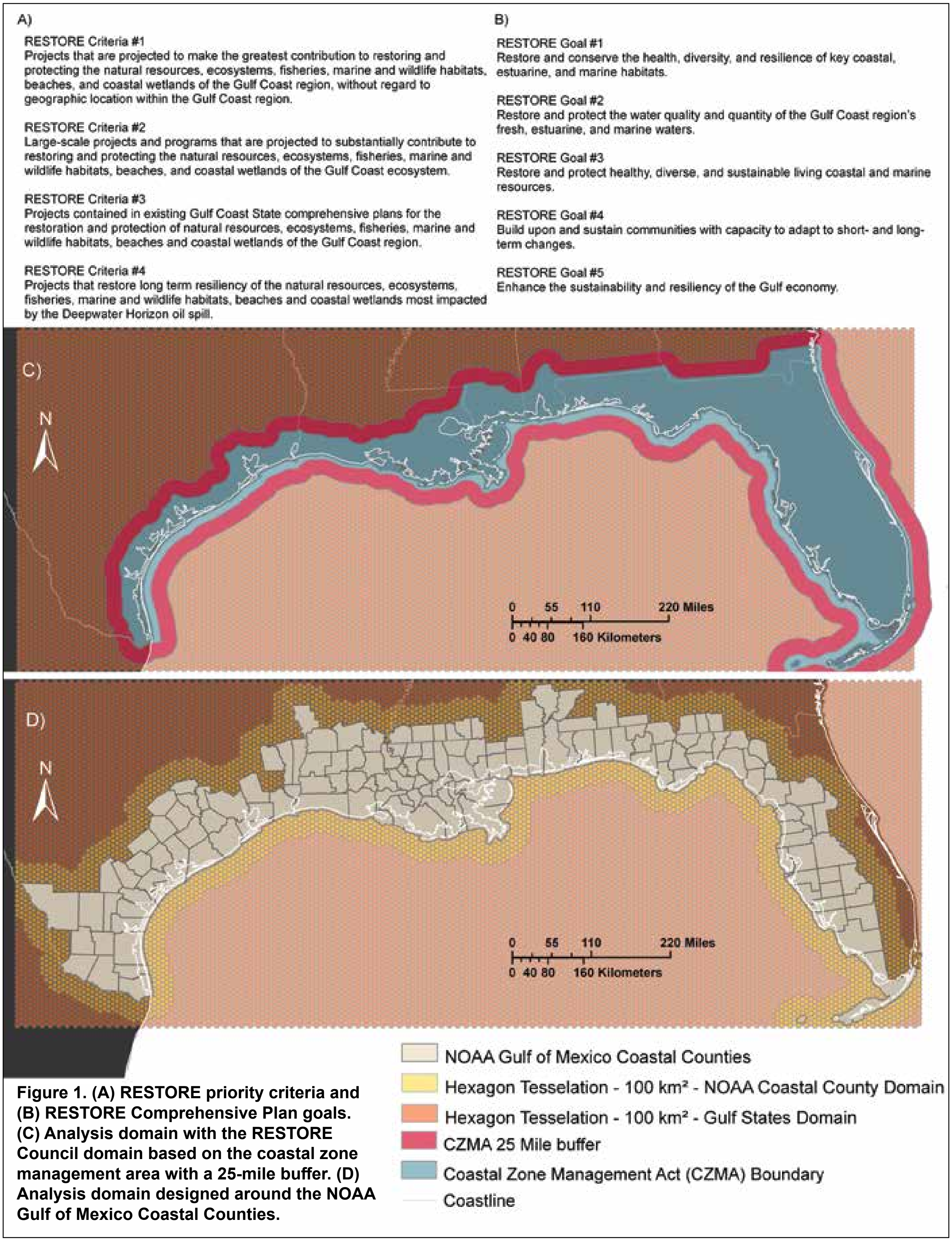

Figure 1. (A) RESTORE priority criteria and (B) RESTORE Comprehensive Plan goals. (C) Analysis domain with the RESTORE Council domain based on the coastal zone management area with a 25-mile buffer. (D) Analysis domain designed around the NOAA Gulf of Mexico Coastal Counties.

addresses this by summarizing threats and potential benefits at the spatial scale relevant to a unique restoration project (Neckles *et al.* 2013).

APPROACH

The selection of appropriate metrics and subsequent compilation of data was achieved through multiple engagements, meetings, and discussions with relevant partners. Subject matter experts (SMEs) from Alabama, Florida, Louisiana, Mississippi, and Texas were recommended by the five states, either from the state's RESTORE Act Center of Excellence (COE) or coordinating with RESTORE Council member agencies. SMEs were engaged to ensure that a BAS approach was taken to identify the location and severity of known and emerging stressors and to account for the relationship between identified stressors and essential ecological services and indicators of human well-being. That information was compiled to help inform future RESTORE Council funded priorities lists (FPLs) related to restoration investments to mitigate those stressors, identify funding from other sources, identify measures/metrics/indicators for success in priority watersheds, and inform adaptive management for future FPLs.

Technical points of contacts were identified from the SMEs in each state and a collaborative literature survey of previous work assessing ecosystem stressors, services, and human well-being was compiled at large spatial scale as well as an integration of smaller scale data sets. Peer reviewed published literature, publicly available government reports, and data summaries were used to clarify key threats, services, and human well-being indicators within Gulf ecosystems, as well as appropriate metrics used to quantify each.

Available knowledge on key metrics and best approaches for documenting primary environmental stressors, services, and indicators of human well-being were cross-walked with the RESTORE Council's five goals and four criteria (Figure 1A, B) outlined in the RESTORE Act (U.S. Congress 2012; Gulf Coast Ecosystem Restoration Council 2016) to provide a list of possible metrics to inform potential restoration investments. Only datasets that could be obtained across the entire northern spatial extent of the Gulf of Mexico were considered. This requirement allowed researchers to develop an accurate Gulf-wide comparison that was not dependent on spatially noncontiguous data as well as data only available within certain regions or political boundaries. The larger dataset was compiled from sources spanning the last decade and is intended to provide a large-scale snapshot comparison. As such, temporal comparisons are not included in this data synthesis.

BOUNDARY AND TESSELATED HEXAGON

To identify the geographic extent for data collation, SMEs and COE staff were asked to provide input on both the overall extent and the most appropriate way to subdivide the project domain. For the overall extent, two primary boundaries were considered: the CZMA boundary with a buffer of 25 miles for the five Gulf states (Figure 1C), based on the RESTORE Act; and the NOAA Gulf states' coastal watershed counties, which provides alignment with the ecosystem, the social (Ache *et al.* 2015; NOAA 2013) and census data (Figure 1D). To provide the greatest utility in data synthesis, the northern Gulf domain was divided using several different classification methods including: ecoregions (Ecoregion III; (Omernik and Griffith 2014)), hydrologic unit code levels (HUC6, 8 and 12), a medium-grained 100 km² tessellated grid, and a fine-grained 1 km² tessellated grid.

Data layers were initially converted to a 100 km² tessellated grid across the entire geographic domain to provide data at a finer resolution than the HUC 12 scale (Figure 1A). Through continued engagement with relevant SMEs, an additional higher-resolution 1 km² hexagon grid was developed to address questions related to mitigation of stressors at a local scale. The final output data layers included both a 100 km² hexagon grid and a 1 km² hexagon grid for threats and ecosystem benefits data layers. This allowed data to be visualized at the broader Gulf-wide scale using the 100 km² hexagon grid and at the 1 km² grid for detailed consideration of specific potential project locations.

STRESSORS

A detailed series of stressor data layers were developed to illustrate not only the spatial range of stressors, but also the variation between types of potential stress to restoration efforts. The interaction between stresses was not analyzed, but data summaries identify areas with multiple stressors. The 40 individual metric primary data layers were summarized into eight stressor categories: human population, *HP*; infrastructure, *IF*; land change, *LC*; pollution, *PO*; Gulf of Mexico water quality, *GOMWQ*; river and estuary water quality, *RWQ*; environmental hazards, *EH*; and invasive species, *IS* (Figure 2A).

To calculate the range of stressor presence within the defined geographic extent, every 100 km² (Figure 2B) and 1 km² hexagon grid was compared to the global mean value for the entire northern Gulf domain using zone-based statistical operations. If the hexagon grid cell's value was greater than the Gulf-wide mean, then that grid cell was categorized as "stress present." Conversely, if the cell's value fell below the Gulf-wide mean then it was classified as "stress absent." This approach of developing a binary threshold rather than one based on ecosystem, regulatory, or management thresholds has been previously applied (Pantus and Dennison 2005). All data summaries are therefore comparative and are appropriate for decision support purposes, but do not provide an independent assessment of ecosystem condition (Carruthers *et al.* 2013; Williams *et al.* 2009).

To develop the eight combined data stressor categories, the number of stressors present within every 100 km² and 1 km² hexagon grid were summed based on stressor category (e.g. the summed infrastructure stressor classification can yield a number between zero and eight). Each stressor category was normalized based on the potential maximum number of contributing variables (Equation 1 & Figure 2B). Differing spatial domains (e.g. smaller than the Northern Gulf of Mexico project domain) were compared using a normalization equation capable

Equation 1. Summed stressor score:

$$score = \left[\left(\frac{RWQ}{10}\right) + \left(\frac{HP}{7}\right) + \left(\frac{IS}{19}\right) + \left(\frac{GOMWQ}{1}\right) + \left(\frac{IF}{7}\right) + \left(\frac{EH}{9}\right) + \left(\frac{LC}{5}\right) + \left(\frac{PO}{4}\right)\right] * 100$$

Equation 2. Summed stressor normalization equation

$$normalization = \left[\frac{(\text{Summed Stressors} - \text{Minimum Summed Stressors})}{(\text{Maximum Summed Stressors} - \text{Minimum Summed Stressors})}\right] * 100$$

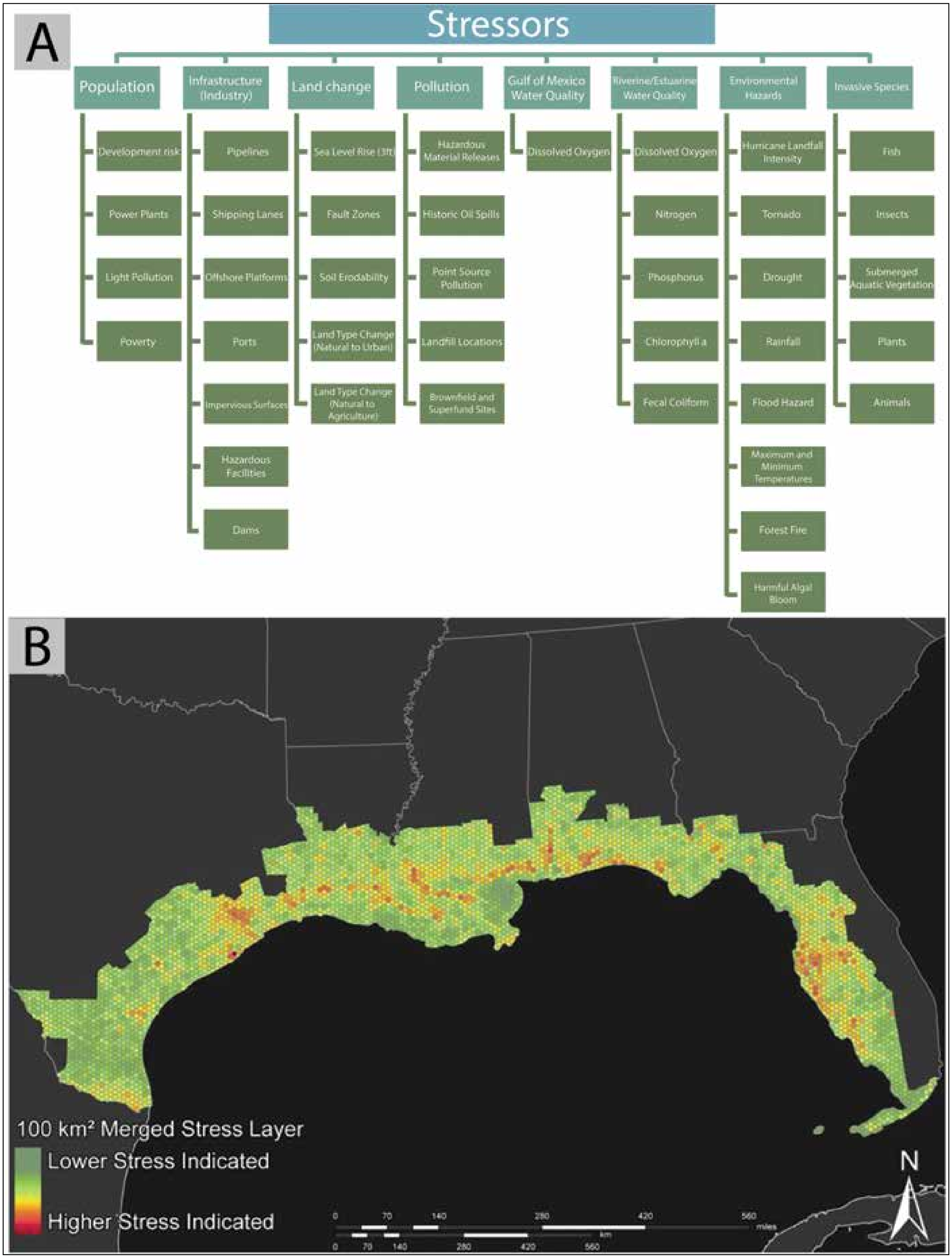

Figure 2. (A) Diagram of the individual metrics within the overall stressor layer showing how the individual layers were accumulated. The lower green layers build together into the second to top teal layer of sub-categories, which combine into an overall stressor layer. (B) Combined stressor layers shown at 100 km² resolution with NOAA coastal county mask.

of accounting for the variation between the maximum and minimum stressor values within the domain extent rather than the total number of stressor variables considered by a given category (Equation 2). Combined layers were all range normalized to a scale between zero and 100.

Equation 3. Well-being index formula:

$$\textit{Well-being Index} = \left[\left(\frac{PCI+EA+NRE+HO+HB+PP}{6}\right) - \left(\frac{PD+P+II+CD}{4}\right)\right]$$

HUMAN WELL-BEING

A series of 10 metrics were identified to indicate human well-being and were summarized into two human well-being categories (Figure 3A): 1) indicators of general well-being, and 2) indicators directly tied to ecological factors. The eight primary metrics related to general human well-being included population density, per capita income, poverty, income inequality, educational attainment, home ownership, chronic disease prevalence (obesity, diabetes and cancer incidence), and healthy behaviors (the propensity of individuals to engage in physical leisure activities) (Cutter *et al.* 2003; Gasper 2007; Haines-Young and Potschin 2010; Ringold *et al.* 2013; Smith *et al.* 2013; Vemuri and Costanza 2006). The two components directly tied to ecological factors were employment in renewable natural resource industries (agriculture, forestry and fishing) and population proximity to recreational greenspaces, wetlands, parks and beaches. Data to assess human well-being were available at either block group, census tract, or county scale, but were downscaled to block groups for further synthesis. Each dataset was continuous and therefore all data across the Gulf were standardized with a z-score. Data were then normalized so that each primary metric was scaled between zero and one.

An overall well-being index of all 10 primary data layers was calculated for each block group across the northern Gulf of Mexico (Figure 3B). This index combines the normalized general and ecological well-being factors by subtracting the average stress value from the average benefit. Benefit categories included: per-capita income, *PCI*; educational attainment, *EA;* natural resource employment, *NRE*; home ownership, *HO*; healthy behaviors, *HB*; and population proximity to greenspaces, wetlands, parks, and beaches, *PP*. Stressor categories included: population density; *PD*; poverty, *P*; income inequality, *II*; and chronic disease, *CD* (Equation 3).

The resultant map (Figure 3B) represents positive and negative values of overall well-being normalized based on the number of contributing variables in both the benefit and stressor well-being categories. Positive values represent higher levels of human well-being (i.e. higher valuations of well-being benefit when compared with well-being stress) and negative values represent high potential reduction in human well-being (i.e. lower valuations of well-being benefit when compared to well-being stress). This layer was mapped at the block group level rather than converting to the hexagonal grid due to concerns associated with generalizing the irregular spatial footprints of census block groups to the standard cell area associated with the hexagonal mesh.

ECOSYSTEM SERVICES (HABITATS)

An extensive list of habitat layers was compiled to help identify areas with high potential for ecosystem services in proposed project locations and how those services may be supported or enhanced by the project. At a local scale, a detailed understanding of the habitat can be used to infer potential ecosystem services (Landers and Nahlik 2013). At the broader Gulf-wide scale these linkages to possible ecosystem services are more generic, and so a compiled habitat layer was used for broad geographic comparison, rather than inferring potential ecosystem services of different locations.

The habitat layers included Land Use Land Cover (LULC), forestry, wetlands, lithology (geology), aquatic environments such as oyster/mangrove/seagrass, rivers/streams, lakes/ponds, protected areas, parks, historical objects/structures/buildings/districts, beaches, and critical habitat for endangered species. The primary sources of data were NOAA, U.S. Geological Survey (USGS), National Wetland Inventory (USFWS), and National Land Cover Database (NLCD). To convert each habitat layer to the 100 km^2 (Figure 4A) and 1 km^2 (Figure 4C, E, G) hexagon grids, the predominant data category (by area) within each hexagon grid was assigned to that entire grid cell. For example, if multiple LULC layers were within a hexagon, but cropland was the dominant layer (by area), the hexagon grid was classified as cropland. This process was replicated for all described attributes at the 1 km^2 hexagon.

With no quantitative summary of potential benefit derived from habitat type, no integrated ecosystem benefit layer was developed. The collated data layers themselves were investigated to inform potential benefits, linkages to stressors and potential for human well-being (Figure 4A-G). To increase ability to interrogate the data at different spatial scales, comparison of the 100 km^2 and the 1 km^2 hexagon grids was necessary (Figure 4A-G). The LULC, National Wetlands Inventory (NWI), and National Hydrography Dataset (NHD) emphasize the importance of presenting multiple layers and different data resolutions to provide the greatest information about ecosystem context and potential benefits at a specific location (Figure 4). Even though it is more computationally demanding to develop, map, and analyze, the benefits of the 1 km^2 hexagon grid (Figure 4C, E, G) can be seen when comparing them directly to the same geographic area summarized by 100 km^2 hexagon grids (Figure 4B, D, F). For these habitat data layers, the main reason to use the 100 km^2 hexagon grid was for presenting very large geographic extents on one map or if development or use of the 1 km^2 hexagon grid was too computationally demanding for available capacity.

APPLICATION

Large syntheses of geospatial data can be used in a wide variety of ways, but as with any data set, context needs to be provided to ensure that the data were used appropriately and that the synthesized data layers are not misinterpreted. At the highest level of synthesis, comparing the combined stressor layer with the combined human well-being indicators suggests that areas of high ecosystem stress do not correlate well with the areas of low human well-being (Figure 2B, Figure 3B).

Coastal Louisiana provides an example of how caution needs to be applied when drawing generalized conclusions, especially when considering large geographic

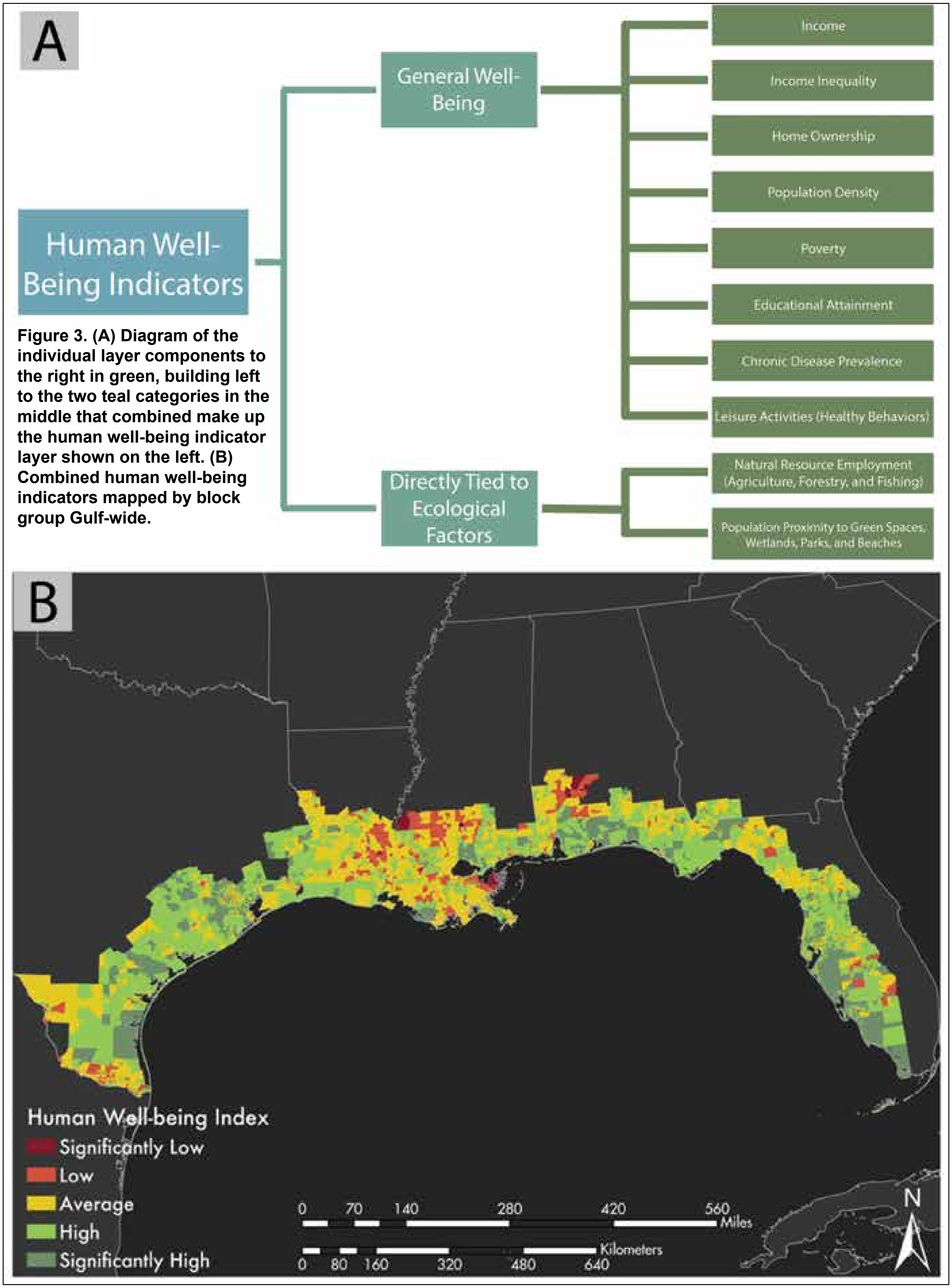

Figure 3. (A) Diagram of the individual layer components to the right in green, building left to the two teal categories in the middle that combined make up the human well-being indicator layer shown on the left. (B) Combined human well-being indicators mapped by block group Gulf-wide.

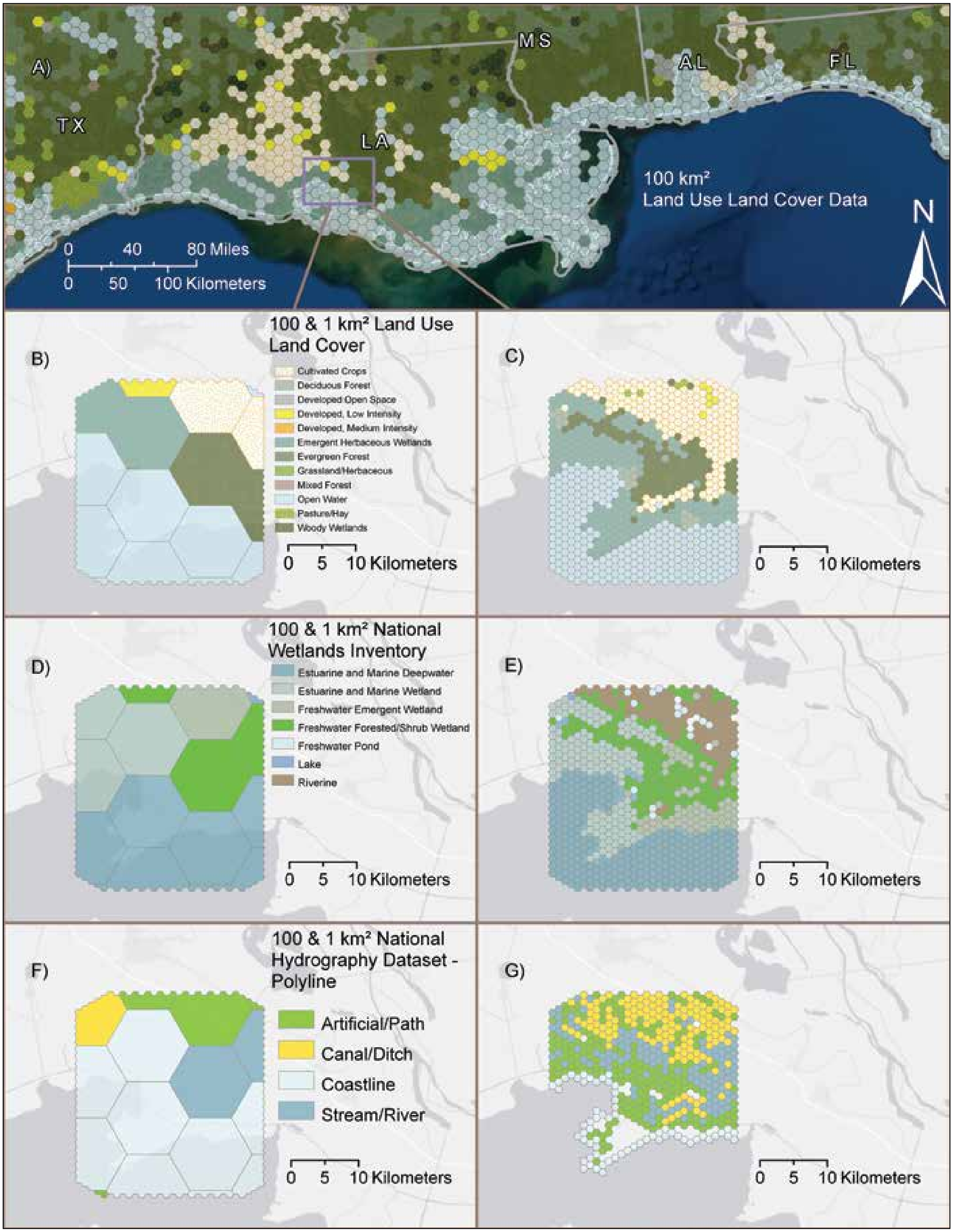

Figure 4. (A) National Land Cover Database (NLCD) habitat layer across the central northern Gulf of Mexico. (B) 100 km² LULC layer at the sample project location. (C) 1 km² LULC layer at the sample project location. (D) 100 km² NWI layer at the sample project location. (E) 1 km² NWI layer at the sample project location. (F) 100 km² NHD Polyline layer at the sample project location. (G) 100 km² NHD Polyline layer at the sample project location (ESRI *et al.* 2019).

areas of data at coarse resolution (Figure 5). While coastal Louisiana is well recognized as threatened due to rapid land loss (Couvillion *et al.* 2016; Day *et al.* 2000, 2011), the 100 km^2 hexagon grid combined stressor map of the northern Gulf of Mexico appears to indicate the shoreline as experiencing low stress (Figure 2B). This could have resulted from inappropriate primary data layers in the analysis, inaccurate primary data, or as a function of data resolution and data presentation.

Looking in detail at three different stress data layers for a 20 km^2 area of the Louisiana coast indicates that the apparent low stress in the 100 km^2 hexagon map is based upon two factors (Figure 5). The first factor is the coarse data resolution when visualized at the 100 km^2 grid scale. The stress score on the 100 km^2 grid is above the scale of impact of many stressors, such that using a spatial average masked out the areas under high stress (Figure 5B in comparison to Figure 5C). Secondly, the specific location of the coastline is important. A highly fragmented coastline such as Louisiana needs the land-water boundary overlain onto the data to highlight that areas classified as "low stress" are on the whole open water and not land. Once the more detailed 1 km^2 grid is presented with the land-water boundary, the area of land along the coastline clearly is represented as highly stressed instead of being categorized as "low stress" (Figure 5). This example highlights that both highly synthetic and broad scale data as well as high-resolution local scale data can be informative, but the correct data scale and resolution needs to be accessed to inform the question being addressed.

With the finer resolution 1 km^2 grid, it is also possible to interrogate the individual data layers to clarify specific potential stressors to a proposed or planned restoration site (Figure 5D-G). The Louisiana coastline, particularly the barrier islands, are mapped as experiencing high potential threat (Figure 5C). The area around Port Fourchon is included within the Louisiana Coastal Master Plan 2017 for marsh creation projects (CPRA 2017) and has localized development within an area of the coast dominated by emergent marsh and open water (Figure 5D). One potential threat to restoration projects being considered in this location is the high density of oil and gas pipelines within the area (Figure 5E). Two other threats are high susceptibility to hurricanes, as documented in the historic hurricane track lines data (Figure 5F), and registered Toxic Release Inventory sites associated with port development (Figure 5G).

DECISION SUPPORT VS. MONITORING AND ASSESSMENT

The approach to summarizing or generating data layers varies based on the intended use of compiled threat, ecosystem, or human well-being metrics data, the number of metrics, and the level of synthesis. A hierarchical reporting structure of "eco-health metrics" has been proposed, whereby elected officials require a low number of highly aggregated indicators to provide simplified guidance to their decision-making. However, environmental managers and the scientific community require a greater number of less aggregated indicators (Harwell *et al.* 2018). Broad geospatial scale data was compiled and developed into least assumption classifications of grid cells above or below the northern Gulf of Mexico mean value to differentiate locations under threat versus those not under threat. This approach can provide high-level decision support and inform initial decisions about broad locations and priorities for restoration, as well as potential for projects to be sustainable or succeed in achieving goals. However, to carry out an assessment of ecosystem condition or analyze specific comparisons between one project site and another, it is necessary to additionally define goals, benchmarks, or thresholds for each primary data layer (DeFries *et al.* 2005; Harwell *et al.* 2018; Longstaff *et al.* 2010). The currently compiled data can also be used to inform monitoring needs, related to known threats to project sites as well as potential ecosystem and community benefits from a project.

SUMMARY LAYERS RELATED TO RESTORE GOALS AND CRITERIA

Each of the three broad layers, both individually and in combination, allow for visualization of potential impacts related to each of the RESTORE Council's goals and criteria (Figure 1A, B). The stressor layer is the most independent, the ecosystem benefits habitat layer and the human well-being layer provide the most utility considered together. Not every location has been monitored to the same capacity (temporally or spatially) so if one stressor appears highly impactful to a project, additional assessment is recommended.

Many of the RESTORE criteria and goals (Figure 1A, B) reference restoring and protecting some type of resource. These layers can help guide that restoration and protection from a project standpoint. Some stressors are not likely to be directly influenced by the project such as road density, infrastructure, shipping lanes, impervious surfaces, subsidence, drought or sea level rise, but the projects could address associated stressors from those such as runoff management or crucial habitat protection or restoration. Other stressors such as land type change or forest fires could be directly and indirectly addressed by a project through its mitigation of impacts from previous disturbances. These project mitigation results could also potentially protect against future conversion.

Water quality impacts a range of resources and is specifically called out in RESTORE Goal 2 (Figure 1B). To understand decisions around restoring and protecting water quality, the stressor layer looks both at potential water quality pollution sources as well as locations where high levels of water quality issues are measured. These water quality components along with the habitat layers, can identify variations in regions and how factors may vary from one project to another to address water quality issues.

From an economic viewpoint as stated by RESTORE Goal 5 (Figure 1B), some of the stressors could be considered positive until a tipping point or threshold is reached. For example, roads and land type change are necessary for access, but eventually impervious surface results in a large range of ecological and human hazards (Conway 2007). Other stressors are likely always going to be detrimental to the resiliency of the economy, such as sea level rise, impaired water bodies, and hurricane landfall intensity. These stressors can be tied to the human well-being layers to begin to understand which populations are already worse off and could be more heavily impacted by stressors.

The human component is critical given many restoration decisions are also made in the context of co-benefits to human populations and is specifically mentioned in RESTORE Goal 4 (Figure 1B). This is in part based on population centers and partially driven by how engaged people are with the natural resources around them. Access or relevance

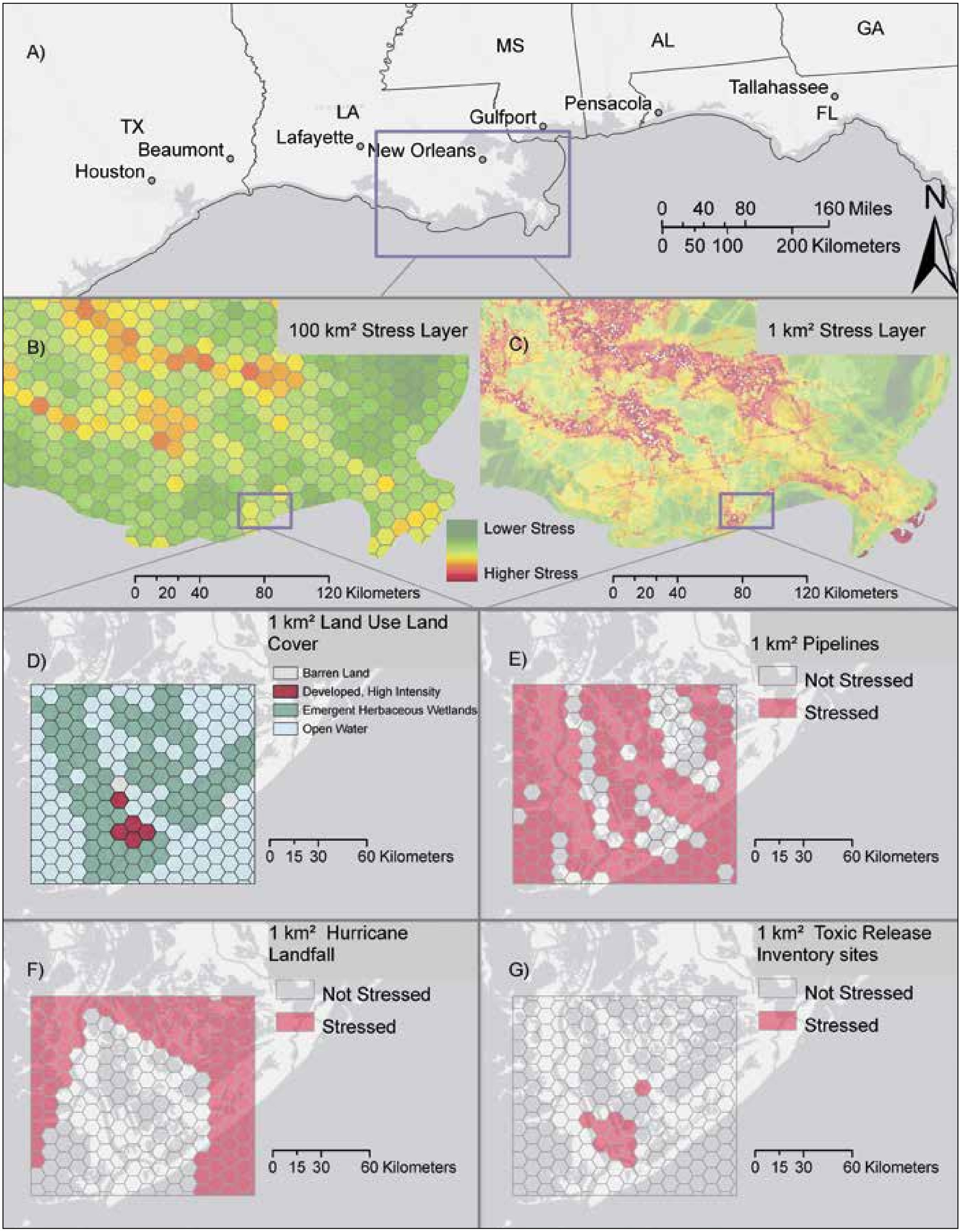

Figure 5. (A) Background reference for project location within the central northern Gulf of Mexico. (B) 100 km² final stress layer at the sample project location. (C) 1 km² stress layer at the sample project location. (D) 1 km² Land Use Land Cover layer at the sample project location. (E) 1 km² pipelines layer at the sample project location. (F) 1 km² Hurricane landfall at the sample project location. (G) 1 km² toxic release inventory site layer at the sample project location (ESRI *et al.* 2019).

to employment can change the perception and political motivation toward those resources. Additionally, different efforts may build upon and sustain communities with capacity to adapt to short- and long-term environmental changes.

The habitat of a project area is crucial to understand direct affects, but regional context is also important (e.g. a wetland surrounded by a forest versus surrounded by a city). From one location to another regional context will change and provides an indication of the range of reasonable outcomes. Different habitats, or benefits of those habitats, are weighted differently by different stakeholders, therefore these layers are not meant to say one project is better than another. Rather, the layers can better inform decision making processes. The context can also help show what projects could be large-scale and compare their contributions, as required by RESTORE Priority Criteria 1 and 2 (Figure 1A).

The RESTORE goal of enhancing and sustaining the Gulf economy (Figure 1B) is best understood through a blend of all the data layers. The human component ties to human engagement with resources that may be protected or utilized based on that interaction. The human well-being layer is further enhanced by the stressor layer to understand variation as well as similarities between impacts to communities. The ecosystem benefits habitat layers can add additional context to show what natural benefits can support the local and broader economy.

Stressors range from sporadic, such as the DWH oil spill, to more systemic ones such as flooding and nutrient loading. Both the human well-being and the ecosystem services habitat layer can be compared to this to understand the resiliency of ecological and human habitats of the Gulf of Mexico. Within the various state comprehensive plans there are references to a range of ecological stressors, important habitats, and human components across the coast. Truly large-scale projects and programs will have impacts beyond the boundary of the specific project area. These Gulf-wide layers provide the added benefit of disregarding state lines and allow for projects and programs that span multiple states.

CONCLUSIONS

Synthesized data regarding potential threats to, and benefits from, restoration investments across the northern Gulf of Mexico can help provide the BAS to restoration planning and prioritization. Compiled data on ecosystem stressors, human well-being, and potential ecosystem benefits at large spatial scales can link restoration goals and objectives to potential restoration outcomes as well as provide a framework to identify programmatic prioritization and monitoring needs. Specific thresholds were not developed in this work and are required to independently assess ecosystem condition and quantify benefits of restoration (Carruthers *et al.* 2013; Neckles *et al.* 2013; Pantus and Dennison 2005; Williams *et al.* 2009). With appropriate use of the data, regional generalizations can be made at the broad gulf-wide scale from the 100 km^2 hexagon grid, while the 1 km^2 hexagon grid can provide local scale information down to the spatial extent of proposed individual projects. By providing geographically explicit BAS uniformly across a broad geographic area, these data layers have potential to inform prioritization of restoration efforts for the northern Gulf of Mexico.

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