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Toward Sustained Monitoring of Subsidence at the Coast Using InSAR and GPS: An Application in Hampton Roads, Virginia

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Abstract Hampton Roads is among the regions along the U.S. Atlantic Coast experiencing high rates of relative sea level rise. Partly to mitigate subsidence from aquifer compaction, Hampton Roads is injecting treated wastewater into the underlying aquifer. However, the GPS (Global Positioning System) station spacing (∼30 km) is too coarse to capture the spatial variability of subsidence and potential uplift from the injection. We present a cost-effective workflow for generating an InSAR (interferometric synthetic aperture radar) and GPS combined displacement product. We leverage a live, open-access archive of InSAR products generated from Sentinel-1 data. We find an overall subsidence rate of \(-3.6 \pm 2.3\) mm/year with considerable spatial variability. The effects of groundwater injection are currently below detection. The workflow presented here is an asset for sustained monitoring of the injection effort and regional subsidence that is applicable along the U.S. coasts for assisting in mitigation and adaptation of relative sea level rise.

Plain Language Summary Hampton Roads in coastal Virginia is among the regions experiencing high rates of relative sea level rise. This rate exceeds the global average primarily due to ongoing land subsidence. In part to reduce this subsidence, Hampton Roads has begun injecting treated wastewater into the underlying aquifer. However, the rate of subsidence and potential uplift from the injection is not uniform but varies spatially, such that the existing network of sensors is unsuitable for monitoring. Here we implement a cost-effective approach for ongoing monitoring that leverages publicly available data products derived from the Sentinel-1 satellite. Overall, we find that Hampton Roads is sinking at a rate of \(-3.6 \pm 2.3\) mm/year, with considerable differences at the neighborhood scale. The effects of the injection cannot yet be seen but will have a larger impact at the surface as more wastewater is injected at full-scale facilities later this year. The workflow presented here is a valuable asset for sustained monitoring of the injection effort and regional subsidence that can be applied along the U.S. coasts for assisting in mitigation and adaptation of relative sea level rise.

1. Introduction

The Hampton Roads area of southeastern Virginia (Figure 1), home to 1.7 million people and many assets of national interest including the largest naval installation in the world, is experiencing the highest rate of sea level rise (RSLR) on the U.S. Atlantic Coast (∼50 cm over the last century Sweet & Park, 2014; Zervas, 2009). As a result of this rise, the occurrence of flooding has increased dramatically in the region over the past 90 years (Ezer & Atkinson, 2014). This significant RSLR occurs not only due to the long-term rise in the ocean associated with anthropogenic global warming but also due to substantial regional subsidence. The regional subsidence is attributed largely to aquifer compaction resulting from groundwater extraction of ∼150 million gallons per day (MGD) and the impacts of glacial isostatic adjustment (GIA), which together contribute more than half of the RSLR (Eggleston & Pope, 2013; Engelhart et al., 2009; Karegar et al., 2016). While a constant rate of regional land subsidence caused by GIA (∼1.3 ± 0.2 mm/year Engelhart et al., 2009) has been assumed (Eggleston & Pope, 2013), a recent study by Bekaert et al. (2017) using synthetic aperture radar (SAR) data showed that the spatial variability of land surface subsidence due to anthropogenic activities should be considered in planning. Neglecting such localized subsidence could have negative consequences in mitigation and adaptation activities, particularly as efforts are already underway to address future RSLR in the region.
Figure 1. Overview of our Hampton Roads study area (dotted inner outline), located in Virginia, USA. Land subsidence accounts for more than half of the RSLR, primarily due to aquifer compaction resulting from groundwater withdrawal (Eggleston & Pope, 2013). The Sustainable Water Initiative for Tomorrow (SWIFT) project aims to reinject 90% of reclaimed wastewater into the Potomac aquifer to increase water availability and alleviate coastal challenges. Initial injection at 1 MGD started on 18 May 2018 and is monitored using an in situ extensometer (triangle marked EXT) measuring aquifer compaction (USGS time series shown in Figure S1). Here, we use GPS (colored markers; blue are used for the geodetic tie-in while gold are used as in independent-check) and InSAR from Sentinel-1 (Path 4; dashed outline) to measure vertical surface displacements especially in response to the injection.

One such effort to mitigate the consequences of RSLR, headed by the Hampton Roads Sanitation District, is the Sustainable Water Initiative for Tomorrow (SWIFT; https://swiftva.com Holloway et al., 2017), which aims to inject 90% (i.e., 135 MGD) of reclaimed wastewater—treated to potable quality—directly into the Potomac aquifer instead of releasing it downstream by 2030. This project aims to (1) increase the fresh groundwater availability, (2) reduce or reverse saltwater intrusion, and (3) contribute to a partial elastic rebound of the aquifer, reducing the rate of land subsidence and thus the rate of RSLR. Since 18 May 2018, SWIFT has been injecting 1 MGD in a pilot well as an initial experiment; the construction of the first of five full-scale facilities begins in 2020, increasing the rate of injection to 135 MGD by 2030 (SWIFT, 2019). To monitor the local effects of the SWIFT project, an extensometer was installed at the pilot well site, which measures the change through time of aquifer thickness (see Figure 1 for location; data available at https://waterdata.usgs.gov/va/nwis/dv?referred_module=sw&site_no=365370762516606&format=gif_mult_sites&PARAMeter_cd=50012&period=365).

Figure S1 in the supporting information shows the aquifer thickness (which is proportional to uplift) time series of the extensometer, which is still too short to resolve the annual cycle but does show the effects of specific events. The thickness of the aquifer increased following the pilot injection start until 18 August when a relatively large amount (∼1.5 mm) of aquifer compaction (proportional to subsidence) occurred. Between 3 and 22 August, injection at the well ceased and was replaced by a groundwater withdrawal (26.6 MG total) in response to the detection of unsafe levels of nitrate in previously injected water (SWIFT, 2018).

While the extensometer provides valuable information about aquifer thickness and thus the displacement of the land surface at the pilot well, it does not provide information about regional subsidence, at locations particularly vulnerable to RSLR. Although Global Positioning System (GPS) stations are available and provide high-precision and high-temporal sampling of the surface displacements in the region (e.g., Argus et al., 2017; Hammond et al., 2012; Kreemer et al., 2016), they are spaced about 30 km apart so cannot resolve horizontal variability of surface displacement at finer scales.
Interferometric synthetic aperture radar (InSAR) can provide surface displacement measurements up to a few meters’ spatial resolution (e.g., Hooper et al., 2012; Jones et al., 2016; Sneed et al., 2003; Shirzaei & Bürgmann, 2018) and thus allows for capturing the spatial variability of the subsidence over Hampton Roads (e.g., Bekaert et al., 2017). The volume of SAR data has been increasing rapidly with the launch of Sentinel-1 in 2014 and will continue to increase with future launches, such as the upcoming NASA-ISRO SAR (NISAR) mission. These data can be processed rapidly with state-of-the-art InSAR techniques, enabling sustained monitoring over large spatial scales. Such ongoing monitoring is particularly important in subsiding coastal regions such as Hampton Roads where flooding continues to worsen with RSLR. Additionally, sustained InSAR analysis of the SWIFT project may provide unique insights into nonlocal effects of groundwater injection on surface displacements through time.

In this study, we combine observations from GPS and Sentinel-1 InSAR to map surface displacement across the Hampton Roads region at 90 m spatial resolution and quantify its corresponding uncertainties. By utilizing InSAR and GPS, we combine the strengths of both data sources and can convert the relative line-of-sight (LoS) InSAR displacement rates into a geodetic reference frame. We investigate locations experiencing high rates of subsidence, which are thus particularly vulnerable to RSLR. We provide an analysis of the region around the SWIFT injection site in an attempt to determine the impact on land surface displacement. In highlighting the SWIFT project, we provide a specific instance of how ongoing monitoring of land surface displacement can be used for developing targeted mitigation and adaptation approaches addressing RSLR. By leveraging a live and open data repository, we demonstrate a strategy for sustained monitoring that can be applied at the many locations experiencing high rates of RSLR along the U.S. coasts.

2. Data

To generate a subsidence map from InSAR, we use Sentinel-1 data acquired by the European Space Agency provided free of charge under the Copernicus program. With a commitment by the European Commission to support the Sentinel-1 constellation at least until 2030, Sentinel-1 is an attractive sensor for sustained monitoring. Over Hampton Roads, Sentinel-1 has acquired data consistently on a 12-day interval since July 2016, leading to 75 acquisitions up to June 2019. The Advanced Rapid Imaging and Analysis (ARIA) Center for Natural Hazards project (Bekaert et al., 2019) provides open and free access to an operational archive of standard Sentinel-1 UNWrapped Geocoded interferogram (GUNW) products, enabling rapid ingestion into postprocessing algorithms. These InSAR-derived surface displacement products are provided as native Sentinel-1 frames and processed at 90 m spatial resolution with interferometric pairs generated between the nearest two acquisitions, leading to temporal baselines of 12 and 24 days over Norfolk. The ARIA project provided additional annual interferogram pairs spanning October and May each year. In our analysis, we use a fully connected network of 163 Sentinel-1 interferograms (equivalent to 163 GUNW products) spanning March 2015 to July 2019 (Figure S2a). We focused our study area on the urban centers of Hampton Roads, which maintain a high signal-to-noise ratio relative to the periphery rural regions (supporting information section S1 and Figure S2b). We combine the high spatial resolution of the InSAR observations with highly accurate, but sparsely distributed (average station spacing of 30 km), GPS observations (see Figure 1 for station locations). GPS provides an important constraint as it allows us to tie the relative InSAR displacement rates into a geodetic reference frame (e.g., Bekaert et al., 2017; Bock et al., 2012; Hammond et al., 2012; Pritchard et al., 2002; Zerbini et al., 2017). We use the MIDAS east/north/up land surface displacement rates and formal uncertainties provided in the IGS14 reference frame by the Nevada Geodetic Laboratory (Table S1; https://geodesy.unr.edu Blewitt et al., 2018).

3. Methods

We use InSAR surface displacement products (GUNW products) generated by the ARIA project, which has been automatically generating SAR-derived data products using the JPL ISCE software (Rosen et al., 2012), as input for our time series InSAR analysis. We leverage the publicly available ARIA tools suite of software (https://github.com/aria-tools) for preprocessing and manipulation of the GUNW products (Bekaert et al., 2019). Although we no longer need to process the InSAR data ourselves, the challenges for time series InSAR related to decorrelation (Zebker & Villasenor, 1992), atmospheric noise (Bekaert et al., 2015; Hanssen, 2001; Murray et al., 2019), and unwrapping errors remain to be addressed (Hooper et al., 2012).
Decorrelation (loss of signal) is introduced due to changes in surface scattering, while atmospheric noise is related to propagation delays in the troposphere and ionosphere. We reduce the impact of decorrelation and atmospheric noise by applying time series InSAR processing using the Miami InSAR Time series software (Zhang et al., 2019). We drop noisy pixels (coherence less than 0.215) and invert our redundant small baseline interferograms to a time series referenced to 10 March 2015. We only consider motion in the vertical, which is the dominant contributor to the LoS in our tectonically stable study area. Further details of the InSAR processing, including uncertainty quantification via bootstrapping (Efron & Tibshirani, 1986), atmospheric corrections (Yu et al., 2018), and masking (Wessel & Smith, 1996) can be found in the supporting information.

During unwrapping, a continuous surface is constructed by adding $2\pi$ moduli to the wrapped phase. Unwrapping between islands is not trivial as water bodies are decorrelated in interferograms. This represents a challenge in Hampton Roads due to the confluence of the Atlantic Ocean and James River, which bisect our study area. We address this by masking out water (see supporting information section S1) and by performing the above time series analysis separately for the regions of land to the north and south of the James River. We then reference the InSAR vertically projected displacement rates for each north/south subregion to local GPS stations to generate a vertical land displacement map. We compute the residual between the region north of the James River and the vertical displacement rate at GPS Station VAHP and apply the offset to shift InSAR pixels accordingly. Although the VAHP time series ended shortly after the Sentinel-1 satellite began acquiring images in 2015, the MIDAS displacement rate ($-1.2 \pm 1.0$ mm/year Kreemer et al., 2016) is dominated by GIA ($-1.3 \pm 0.2$ mm/year Engelhart et al., 2009). This is a strong indication that the displacement rate estimated at VAHP is maintained through the end of our analysis in June 2019. As an additional check, we referenced the region north of the James River to station LNG4 and found agreement within uncertainty (not shown).

In the southern region, several of the GPS stations—especially LOY2 and SPVA—suffer from noise, data gaps, and/or short records. To address these challenges, we combine the displacement rate at Station LOY2 with an average residual, weighted by GPS uncertainties, between each of the GPS stations and its surrounding InSAR pixels. We only use GPS stations that have temporal overlap and coherent InSAR pixels within a 300 m radius: LOY2, LS03, LOYZ, and SPVA (blue squares in Figure 1). We also apply a correction to the individual time series of InSAR displacement histories to show the deformation of the pixel in the IGS14 framework. As the InSAR time series processing is done relative to local GPS stations, the corrected displacement history can be obtained by adding in local GPS displacement history, which we reconstruct over time by multiplying the GPS displacement rate with the duration of the InSAR time series. Although this does not provide an absolute reference to IGS14, it allows us to make a comparison between the IGS14 displacement rate maps and the corrected InSAR displacement history.

4. Results

Our regional vertical displacement rate map with corresponding uncertainties as derived from Sentinel-1 data, spanning March 2015 to June 2019, and GPS referenced to the IGS14 reference frame is shown in Figure 2. Square colored markers show the vertical displacement rate of the GPS stations used as a tie-in for InSAR. We find good agreement between InSAR and GPS with a root-mean-square error (RMSE) of 0.9 mm, for all stations within our study area (see Table S1 for individual station residuals). On average we find Hampton Roads to be subsiding with a vertical displacement rate of $-3.6 \pm 2.3$ mm/year, Norfolk with a displacement rate of $-4.4 \pm 2.5$ mm/year, and Virginia Beach with a displacement rate of $-3.8 \pm 2.5$ mm/year.

Within our study area, we find 85.7% of our estimated displacement rates to be significant at 1-sigma confidence. This includes nearly all of Norfolk, Virginia Beach, and Hampton (Figure S3). We additionally find 12.5% of our displacement rates to be significant at 2-sigma confidence, correlating with subsiding residential areas in Norfolk and Portsmouth. Uncertainty increases with distance from the reference GPS stations, resulting in increased error along the coast in south of the James River and in western rural areas.

To highlight particularly important sections of Hampton Roads, we draw three transects through the regions (Figures 3a–3c). Transect a-a starts in the northwesternmost part of our study area, extends southward through station VAHP, and ends at GPS Station LOY2. Both the subsidence and unwrapping errors (discontinuities) at Craney Island are apparent. Hampton and Newport News show relative stability. Transect b-b
Figure 2. Vertical displacement rate map (a) and corresponding 1-sigma uncertainties (b) as estimated from Sentinel-1 derived interferograms spanning March 2015 to June 2019. To minimize long-wavelength noise, we tie displacement rates on the upper peninsula to GPS Station VAHP. Southern displacement rates are tied to station LOY2 combined with an average residual, weighted by GPS uncertainties, between each of the GPS stations and its surrounding InSAR pixels. The square and circular markers correspond to GPS stations used and not used, respectively, for the IGS14 tie-in of the InSAR displacement rates.

begins at First Landing State Park, runs southwest through central Virginia Beach and Norfolk, and ends at GPS Station LOY2. The entire transect is subsiding, especially at First Landing State Park and in many densely populated suburban regions. Transect c-c begins at Smithfield near GPS Station LOYZ. It extends across the James River into Hampton, crossing GPS Stations DRV5/6, VAHP, and LNG4. There is good agreement with all the GPS stations despite the high spatial variability along the transect, and a loss of coherence in the rural areas of the southwest and northeast.

Specific locations subjected to further time series analysis (Figures 3d–3g) are marked as follows: (d) Central Hampton, (e) Norfolk Naval Shipyard, (f) Craney Island, and (g) First Landing State Park. To reduce noise in the time series, we average the displacement history of all pixels within a 400 m radius around each of the individual locations. We then difference this time series with the displacement of the InSAR values near the closest GPS station to reduce long-wavelength atmospheric noise. For further validation, (b)–(d) were also differenced to the second-closest GPS station, with similar results (Figure S4). With the exception of the Central Hampton, where no displacement is found, the displacement rates show subsidence trends that are significant at the 1-sigma level.

To assess the impact of the SWIFT pilot injection project on local displacements, we compare the vertical displacement at the injection with that of the surrounding area (Figure 4). We reference the relative InSAR displacement rates to the location of the injection site and difference the spatially averaged displacement history within the cyan torus with that near the injection site (magenta circle). The injected waters will spread through the Potomac Aquifer (McFarland & Bruce, 2006); thus, any impact on subsidence will manifest as an uplifting trend near the injection site relative to the surrounding area.

The overview panel (Figure 4a) shows the data that have been used in the comparison. The magenta circle and cyan torus each have a radius of 1 km and are separated by 7 km. Craney Island, Newport News, and Isle of Wight are omitted from the regional analysis as compaction of the Craney Island reclamation site and potential unwrapping errors linking Portsmouth, and Newport News/Isle of Wight could bias the comparison. In addition to the configuration shown in the overview plot of Figure 4a, we test a variety of radii lengths for the inner circle and outer torus and distances between them (Figure S5). We do not yet observe surface uplift induced by the injection in our experiments.

5. Discussion

Our study provides information on vertical displacement between 2015 and 2019. Earlier InSAR studies have focused on the period between 1992 and 1998 (Simone & Wdowinski, 2020), 2007 and 2011 (Bekaert et al., 2017), and 2011–2017 (Morgan et al., 2017). In agreement with these studies, we find the subsidence
Figure 3. (a–c) Transects across the regional vertical land displacement map highlight spatial variation in surface displacements across Hampton Roads for the period March 2015 to June 2019. The 1- and 2-sigma InSAR uncertainty is shown with dark and light gray shading, respectively, along each transect. Each measurement along the transect is obtained by including the InSAR displacement rates within a 500 m radius about the point along the profile. Two-sigma vertical GPS displacement rates are colored blue if used in the referencing and gold otherwise. (d–g) Vertical displacement history of locations (shown in inset map) in the IGS14 geodetic reference frame. InSAR observations (black markers) are averaged within a 300 m radius around each location and weighted by the uncertainty. The linear least squares displacement rate is shown by the red dashed line, with both the magnitude and 1-sigma uncertainty reported within each panel.
to spatially vary across Hampton Roads, with exceptionally high displacement rates occurring at Craney Island and First Landing State Park. Our vertical displacement rates fall within the uncertainties of Morgan et al. (2017), increasing our confidence in the results. Although not directly comparable due to the difference in time intervals, our findings along the transects agree well with those found by Bekaert et al. (2017), with displacement rate uncertainties improving by a factor between 2 and 3 (Bekaert et al., 2017, Figure S6). Unlike Bekaert et al. (2017), our study does not apply a full-resolution persistent-scatterer approach; instead, we apply Small Baseline processing leveraging multilooked 90 m products as provided through the JPL ARIA project, increasing our signal to noise ratio and enabling sustained monitoring as new Sentinel-1 images are acquired.

Our transects (Figures 3a–3c) highlight the subsidence occurring along the banks of the Elizabeth and Lafayette rivers, which are notorious for flooding, both due to regular tides and events including storm surges and prolonged rainfall. We also find neighborhoods near the Norfolk/Virginia Beach border that experienced recent prolonged flooding caused by Hurricane Matthew to be subsiding. The time series analysis (Figures 3b–3f) highlights the surface displacement occurring at several points of interest. As with our previous study (Bekaert et al., 2017), we observe a hot spot of subsidence on Craney Island, which is a land reclamation site. In contrast, we observe the stabilization of the Norfolk Naval Shipyard, which previously had been subsiding at a rate of ∼10 mm/year. Loading operations at the shipyard ceased at the end of 2010, explaining the stability for the current sensing period (March 2015 to June 2019). Coastal Virginia Beach is a regionally important economic driver that is subsiding at rates between 2 and 6 mm/year, with the fastest subsidence rates in First Landing State Park and the wetlands along the northern boundary of Back Bay National Wildlife Refuge.

The considerable scatter about the trends at locations (e)–(g) (Figure 3) is driven by both the scattering and tropospheric noise in the data. Sentinel-1 operates at C-band and thus is more sensitive to vegetation induced decorrelation noise than the ALOS L-band data used in Bekaert et al. (2017). Although the GUNW products used in our analysis are multilooked to a 90 m resolution to increase the signal-to-noise ratio, pixels along water bodies are affected by averaging both water and land, which leads to increased noise that can be observed in our time series analysis of Craney Island and First Landing State Park. Additional scatter can be observed as a result of tropospheric noise, which increases away from the reference GPS tie-in station (see Figure S7).

As a first-order investigation into the relative contributions of GIA and anthropogenic drivers of land surface displacement, we remove the GIA model value of $-1.3 \pm 0.2$ mm/year from our displacement map and propagate the uncertainty (Figure S8 Engelhart et al., 2009). We find an overall anthropogenic subsidence rate in Hampton Roads of $-2.3 \pm 2.4$ mm/year, with $-3.1 \pm 2.5$ mm/year in Norfolk, and $-2.5 \pm 2.5$ mm/year in Virginia Beach. While the anthropogenic displacement rates are largely driven by groundwater extraction, the complex hydrogeologic framework underlying Hampton Roads combined with the paucity of groundwater level data prevents a simple attribution of surface displacement to groundwater extraction rates (Eggleston
Recurrent Flooding Resiliency the Commonwealth Center for also supported through funding from Institute of Technology, under a Propulsion Laboratory, California a carry out a part of the Jet anonymous reviewers. The research observations. We appreciate the maintaining the networks and sharing community, NOAA, and ODU for (GUNW) products. We thank the GPS standard InSAR displacement USGS, and ARIA for processing and GPS data use in this study, the extensometer data provided by the USGS, and ARIA for processing and providing open and free access to standard InSAR displacement (GUNW) products. We thank the GPS community, NOAA, and ODU for maintaining the networks and sharing observations. We appreciate the insightful comments provided by two anonymous reviewers. The research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. B. B. was also supported through funding from the Commonwealth Center for Recurrent Flooding Resiliency (CCRFR).

& Pope, 2013; McFarland & Bruce, 2006). However, recent studies have shown correlations between groundwater extraction and land surface subsidence in Hampton Roads and highlighted the role of diverse spatiotemporal processes in driving coastal flooding (Karegar et al., 2016, 2017).

While we were unable to observe land surface uplift as a response to the SWIFT injection at the current time (Figures 4 and S5), we have developed here a methodology capable of doing so in the future. Given that injection has only been ongoing for 16 months (at time of analysis), the time series is not long enough to separate a signal from the surrounding noise (e.g., Blewitt & Lavallée, 2002). Further, the injection rate of 1 MGD is a fraction of the regional groundwater withdrawal rates of ~150 MGD (Heywood & Pope, 2009; Holloway et al., 2017). More injections sites are under construction as the SWIFT project advances past the pilot stage, and we expect the combination of a longer time series and greater injections rates to counteract the regional withdrawal and manifest as land surface uplift observable by InSAR.

Although valuable for many purposes, the GPS network is too spatially sparse for capturing the regional variability of subsidence in coastal settings. InSAR is able to bridge this knowledge gap, and with the continued acquisitions made by Sentinel-1, our confidence in the displacement rates will improve. Here we have established a cost-effective workflow for generating the time series InSAR product necessary for such monitoring. By leveraging the operational archive of standard InSAR displacement products from the ARIA project, we are able to rapidly conduct and seamlessly update our time series InSAR analysis as new acquisitions become available.

Our study demonstrates a specific value for sustained monitoring of surface displacements in relation to mitigation and adaptation of RSLR by evaluating the ongoing SWIFT project in Hampton Roads, Virginia. More generally, the ARIA archive covers much of the North American coastline, such that our strategy is applicable in the many other communities experiencing high rates of RSLR. Detailed subsidence knowledge is essential for developing targeted policy and engineering solutions that increase resilience in the most vulnerable neighborhoods. In addition to providing this information, our approach enables continual evaluation and—if necessary—adjustment of the implemented solutions to best respond to the ongoing threats of RSLR.

Data Availability Statement

ARIA standard products are retrieved from the ASF DAAC, which are provided through the NASA Earth Science Data and Information System (ESDIS) project, referenced in text as Bekaert et al. (2019). GPS data are retrieved from the Nevada Geodetic Lab, referenced in text as Blewitt et al. (2018). The rate and associated uncertainty map produced in this work are accessible through the Digital Commons at Old Dominion University, a FAIR certified repository, and are included in the supporting information.

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