Ingestion of Simulated SMAP L3 Soil Moisture Data into Military Maneuver Planning

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ABSTRACT
This paper uses simulated SMAP level-3 (L3) soil moisture data to calculate soil strength directly and compares the results against the current Noah Land Information System–based climatology approach. Based on the availability of data, three sites were chosen for the study: Cheorwon, South Korea; Laboue, Lebanon; and Asham, Nigeria. The simulated SMAP satellite data are representative of May conditions. For all three regions, this is best represented by the “average” soil moisture used in the current climatology approach. The cumulative distribution frequency of the two soil moisture sources indicates good agreement at Asham, Nigeria; mixed agreement at Cheorwon, South Korea; and no agreement at Laboue, Lebanon. Soil strengths and resulting vehicle speeds for a High Mobility Multipurpose Wheeled Vehicle (HMMWV) M1097 were calculated based on the Harmonized World Soil Database soil types used by the two soil moisture sources, as well as with a finer-resolution National Geospatial-Intelligence Agency product. Better agreement was found in soil strengths using the finer-resolution soil product. Finally, fairly large differences in soil moisture become muted in the speed calculations even when all factors except soil strength, slope, and vehicle performance are neglected. It is expected that the 0.04 volumetric uncertainty in the final SMAP L3 soil moisture product will have the greatest effect at low vehicle speeds. Field measurements of soil moisture and strength as well as soil type are needed to verify the results.

1. Introduction

a. Mobility modeling

Having to move people and supplies both on and off roads in any weather is not a new problem. Formal investigations of military ground vehicle mobility problems began during World War II as a result of vehicle immobilization in soft soil (Rula and Nuttall 1971). During the 1950s and 1960s, in addition to tire–ground interaction, slope, obstacles, and driver reaction were incorporated into mobility predictions. Rula and Nuttall (1971) compared 10 off-road single vehicle models that included driver response to vibration and vehicle–terrain interaction. They found that none of the models did well in capturing vehicle vibration responses but that the simple U.S. Army Waterways Experiment Station (WES) vehicle cone index (VCI) outperformed the more complicated Bekker/Tank-Automotive Command (TACOM) Land Locomotion Division models for characterizing vehicle–soil interaction. Rula and Nuttall (1971) also proposed that the WES model should be the Army’s choice because it is the most complete and, since most of the submodels were developed from field test data, the most realistic.

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Based on the *Rula and Nuttall (1971)* study, the Army Materiel Command (AMC) funded development of the AMC ’71 mobility model. This model combined the efforts of WES, TACOM, and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL; *Fatherree 2006*). The outcome of this project included the establishment of a comprehensive computer program that implements the model and “allows for the development of quantitative information on the mobility of a given vehicle in a selected geographic area” (*U.S. Army 1973*, p. 3). AMC ’71 was mainly used to assess off-road performance design considerations for new vehicle development. The AMC ’71 model was soon followed by AMC ’74. Major revisions included vehicle performance on slippery soils, muskeg, and shallow snow; improved driver behavior; travel on paved roads; and upgrades to the computer code (*Jurkat et al. 1975b*). AMC ’74 was intended only as an interim until what is considered the second-generation Army Mobility Model (AMM-75) could be released (*Jurkat et al. 1975a,b*).

The North Atlantic Treaty Organization (NATO) adopted AMM-75 in 1977 and changed the name to the NATO Reference Mobility Model (NRMM; *Fatherree 2006*). The three main user groups for NRMM are vehicle developers, vehicle procurement, and vehicle users (*Haley et al. 1979; Ahlvin and Haley 1992*). For a given vehicle, NRMM first calculates the maximum speed across a terrain unit for each factor (slope, vegetation, surface roughness, soil strength, etc.) and then takes the minimum of these as the allowable speed. These speeds can then be linked using secondary algorithms (*Haley et al. 1979*).

### b. Soil strength

One of the many terrain factors needed to determine vehicle speed is soil strength. For vehicle mobility modeling, the soil strength is quantified using either the cone index (CI) or rating cone index (RCI), both of which are indicators of soil shear strength. The unit of measurement is pressure. Cone index is defined as the force per unit area required to push a 30° stainless steel cone penetrometer through a specified thickness of soil (*Meyer et al. 1977*). RCI is the CI corrected by a remolding index (which ranges from 0 to 1) and is used for fine-grained soils such as clays and silts. It is considered to better represent the soil subjected to traffic. The remolding index is the ratio of the CI after remolding to the original CI. Remolding is achieved by tamping a 50.8 mm (2 in.) radius by 152.4 mm (6 in.) high cylinder of soil with a 1.14 kg (2.5 lb) remolding hammer dropped from a height of 0.3 m (12 in.) 100 times for fine-grained soils and 25 times for sands with fines (*Shoop 1993*). CI and RCI can be measured on site with a standard trafficability kit (*Stevens et al. 2013*). However, areas of interest for military operations are frequently located in remote and hostile places. Therefore, CI and RCI have also been estimated based on other available data. Based on a large number of field and laboratory strength tests on soil collected from over 1000 sites, the Geotechnical Laboratory at WES developed a set of empirical equations to predict both CI and RCI as a function of soil moisture and Unified Soil Classification System (USCS; *Sullivan et al. 1997*). Unlike the U.S. Department of Agriculture (USDA) soil texture scheme that is based only on grain size distribution, the USCS also includes the engineering properties plasticity index and liquid limit to further characterize silts and clays. There is no one-to-one correlation between the two systems.

Efforts to link strength to percent sand, silt, clay, and bulk density as well as water content are mixed. Based on data from 16 locations collected by different researchers, *Kumar et al. (2012)* found almost no correlation between CI and the different soil properties if considered separately, but they did find fair comparison ($r^2 = 0.47$) if they combined percent sand, moisture content, and depth. *Fulton et al. (1996)* also found poor correlation between CI and bulk density for a silty clay loam. *Chung et al. (2013)* found mixed results when they investigated using a tractor-based electrical conductivity sensor that measures soil strength at five evenly spaced depths down to 50 cm to standard CI methods both theoretically and empirically based on field tests. They concluded that further work on the effects of soil texture and moisture was needed, as well as additional insight into the relationship between the two methods.

The VCI was developed by the U.S. Army specifically to assess a vehicle’s ability to traverse soft-soil terrain (*Priddy and Willoughby 2006; Stevens et al. 2013*). It is a measure of the soil strength required for mobility. VCI was developed by WES and is defined as the minimum soil strength necessary for a self-propelled vehicle to consistently make a prescribed number of passes (typically 1 or 50) in a level, nonslippery straight lane without becoming immobilized (*Priddy and Willoughby 2006; Stevens et al. 2013*). The International Society for Terrain-Vehicle Systems specifies that VCI = $f$(CI) for coarse-grained soils while VCI = $f$(RCI) for fine-grained soils (*Meyer et al. 1977*). The VCI metric is one of the most significant outcomes of WES’s trafficability studies (*Priddy and Willoughby 2006*).

### c. Soil moisture

NRMM requires USCS soil type and soil strength as inputs. Soil strength can be estimated from soil moisture when direct measurements of RCI are unavailable. Often, the areas of most interest to the Army are hard to
get to and large, making on-the-ground measurement difficult, if not impossible. Soil moisture can be predicted based on a combination of precipitation and environmental data. Sources of precipitation data in order of preference are onsite measurements, then long-term monthly histories. Historically, if neither of these was available, a method developed by Bullock (1994) was used to infer the strength using USCS soil type, terrain slope, and the Trewartha (1968) climate zones. The 13 Trewartha (1968) climate zones are a modification of the Köppen system and are based on vegetation distribution and average annual and monthly precipitation. Bullock (1994) averaged the climatology rainfall for each geographic area over the Trewartha (1968) climate zones to provide worldwide monthly values. Based on the terrain slope and the climate zones, Bullock (1994) then assigned a wetness index (from 0 to 5, from arid to saturated, respectively). The wetness index is used by NRMM as an indicator of depth to water table, minimum/maximum water content, and soil drainage potential. Bullock (1994) also provided tables for expected seasonal RCI values in each climate zone for each combination of soil wetness index and soil type. While the Bullock (1994) method is based on generalization of climate zones, it does depend on higher-resolution soil type and slope data. This method has been used to provide soil strength estimates when minimal data are available. It should be emphasized that it does not account for individual precipitation events. Further, future use of this method should incorporate updated climatologies.

Recently, Baylot et al. (2013) began to use computer-modeled soil moisture to determine soil moisture climate from which RCI is calculated using the relationships of Sullivan et al. (1997). Soil moistures are generated at 1-km resolution by running a land surface model [in this case, the community Noah land surface model (LSM; Chen et al. 1996; Ek et al. 2003) within Land Information System (LIS; Kumar et al. 2006, 2008; Peters-Lidard et al. 2007)] for a period of time (usually 5 years). From this time period, soil moisture maps are constructed to represent four climatological conditions: the “dry” (driest 30-day period in an average rainfall year), “average” (average 180-day period in an average rainfall year), “wet” (wettest 30-day period in an average rainfall year), and “wet-wet” (wettest 10 days for a year having 150% or greater of average rainfall) periods (Bullock 1994; Baylot et al. 2013). While this method can potentially provide finer-resolution information than the SMAP data, this method still does not account for specific weather events.

Another approach is to use land surface models such as Noah (Chen et al. 1996) and Fast All-Season Soil Strength (FASST; Frankenstein and Koenig 2004a,b, 2008) to calculate soil moisture and hence soil strength as a function of forecasted weather. The ability of the models to accurately predict soil moisture at a location strongly depends on the quality of the precipitation forecast and the scale of the underlying terrain information. Currently, the scale of the forecast data is 1–15 km. These problems can be partially mollified with assimilation of observations (whether ground based or remote; Margulis et al. 2002) and by downscaling techniques (Sahoo et al. 2013).

Zreda et al. (2008) measured soil moisture on the hectare scale with a noninvasive ground-based probe that captures cosmic-ray neutrons. They found that the fast neutrons are well correlated to soil moisture content because of the interaction of the neutrons with the hydrogen in the soil and water and are fairly insensitive to soil type, although the probes need to be calibrated at each site because of differences in soil chemistry. Desilets et al. (2010) showed how the probes could be mounted on vehicles to get measurements over transects. Since the probes are sensitive to local soil chemistry, how to calibrate the sensors needs to be addressed. Also, although better than single-point handheld probes, they only provide data where probes already exist or in vehicle accessible areas. A project has just begun to determine if vehicle-mounted cosmic-ray sensors can be used to predict soil moisture for mobility studies, including how to calibrate them for variable terrain and vegetation conditions.

Airborne remote methods have included gravimetric, passive and active microwave, optical, and thermal infrared (Wang and Qu 2009). Of these, the microwave approaches are the most promising. The gravimetric spatial resolution is too coarse for military purposes, while the optical and thermal require clear conditions. The NASA SMAP mission will measure in the L band (1.26 GHz active, 1.4 GHz passive). The resolutions are 3, 9, and 36 km for the active, combined active–passive, and passive products (Entekhabi et al. 2012) and are much better than current or past satellite missions. The data latency is 24 h at best, and the revisit rate is 1–2 days. L-band measurements are limited to the upper 4–5 cm of the soil column. The critical layer for ground vehicle mobility is often 15–30 cm below the surface. However, the soil moisture in this layer is related to the surface soil moisture. Because of this and the fact that 3 km is still coarser than what is needed by the Army to accurately predict mobility parameters, either a way to downscale the data or a way to ingest the information into numerical models is needed.

Other than directly using the observed soil moistures from the satellite-borne instruments, these data are often assimilated into numerical models vis-à-vis more
sophisticated approaches, including, for instance, the ensemble Kalman filter (Margulis et al. 2002). This can help address both the data latency problem (through better informing the latest analyses or forecasts through influence of assimilated information on model state evolution) and the resolution dilemma. This is how we plan on eventually using the SMAP products.

The aim of this study was to investigate the differences in mobility predictions in data-sparse and/or denied areas when using the current Noah LIS–based soil moisture climatology method of Baylot et al. (2013) versus using simulated SMAP combined soil moisture products directly. To do this, we first compare the associated soil moistures themselves, and then investigate the estimated soil strength. Finally, we compare the computed vehicle speed maps with the two methods. Three international sites as outlined in the next section are used to analyze our findings. To eliminate the effects of other variables that affect vehicle speeds, all features (surface roughness, vegetation, etc.) are removed except for soil type and slope.

2. Test sites

Three sites were chosen to investigate the effect of using simulated SMAP level-3 (L3) soil moistures to calculate soil strength and the resulting effect on vehicle performance as measured in terms of speed. All sites are included in other mobility studies to provide off-road mobility predictions at different locations as a reference standard for future operations (Baylot et al. 2013; Green et al. 2014). These sites have the necessary terrain data and also simulated SMAP satellite data. While an effort was made to reasonably represent the necessary terrain factors, the terrains should be considered geotypical models of the kinds of terrain that are expected in these areas, rather than completely geospecific models of the precise locations described. The three sites chosen for the study are Cheorwon, South Korea; Laboue, Lebanon; and Asham, Nigeria. For all three areas, we obtained soil type information from the Vector Product Interim Terrain Data (VITD) provided by the National Geospatial-Intelligence Agency (NGA).

a. South Korea

The Korea site is located in northern South Korea near Cheorwon, South Korea, between 38°N, 127.2°E and 38.25°N, 127.58°E (Baylot et al. 2013). It is approximately 27 km × 27 km. The area is characterized as hilly, with elevation ranging from 125 to 1250 m, as seen in Fig. 1. Vegetation ranges from open fields/cropland to dense forests. About half of the area is sparsely forested with trees of 0.1-m diameter spaced greater than 30 m apart (Green et al. 2014). The soil in this area is predominately silty sand (SM) and inorganic clay of low–medium plasticity (CL; Fig. 1). The Trewartha (1968) climate zone classification is humid subtropical (Cf).

b. Lebanon

The site in Lebanon is centered on the Beqa Valley, with the Lebanon Mountains to the west and the Anti-Lebanon Mountains to the east, in the northeast section of the country (Fig. 2). The area is about 15 km × 15 km (Green et al. 2014), ranging from 37.18°N, 36.30°E in the southeast to 34.31°N, 36.46°E in the northwest. Elevations range from 700 m in the Beqa Valley to 1460 m in the Anti-Lebanon Mountains in the southwest corner of our area. The town of Laboue is in the southwest corner. To the northwest of Laboue are irrigated fields. Except for a small region in the northwest where there is a small forest, the area is otherwise bare. The Trewartha (1968) climate zone classification is dry summer subtropical (Cs).
The soil information is from the NGA VITD dataset and is classified using the USCS schema (Fig. 2). There is a definite northeast–southwest banding of the different soils. The Beqa Valley consists mostly of inorganic silt of high plasticity (MH). The Lebanon Mountains are CL, except in the forested region where it is SC. The Anti-Lebanon Mountains progress from clayey gravel (GC) in the lower elevations to a SM with some ML in the lower regions.

c. Nigeria

The site near Asham, Nigeria, is considered a plateau. It ranges from 10.29°N, 8.15°E in the southeast to 10.42°N, 8.28°E in the northwest, and the elevation ranges from 200 to 250 m (Fig. 3). Like the Laboue, Lebanon, site, the area of interest is about 15 km × 15 km (Green et al. 2014). Unlike the other sites, the Nigeria area is fairly flat. Heavy vegetation covers 17% of the region (3 m or less stem spacing), while the remaining area has less dense coverage (30 m or less stem spacing; Green et al. 2014). Unlike the other study plots, the surface soil is all CL, except for a few rock outcrops (Fig. 3). The Trewartha (1968) climate zone classification is tropical savannah (Aw).

3. Procedure and data sources

a. Soil data

For all three areas, we obtained USCS soil type information from the VITD provided by NGA for the vehicle speed calculations. These are legacy data and have been used for mobility analysis for many years. The data have a nominal resolution of 100 m.

The simulated SMAP and Noah LIS soil texture data are from the Harmonized World Soil Database (HWSD). The SMAP data are located on the SMAP Science Data System (SDS). The HWSD only classifies soil using the agricultural system, not the engineering system used to determine strength. There is no one-to-one mapping from one system to the other. Thus, further error is introduced converting from one system to the other. How to do this is a research topic in its own right. For all three areas of interest, the HWSD original data source is the Food and Agricultural Organization (FAO), so the resolution is 50 km.
The SMAP HWSD data are resampled to the 9 km Equal-Area Scalable Earth (EASE) fixed grid using simple linear averaging (Das 2013). The attributes used for the SMAP SDS are topsoil sand fraction, clay fraction, and bulk density, as they are needed to compute the dielectric constant in the soil moisture retrieval algorithms (Das 2013). These data were not used directly for this study.

We converted the HWSD soil types to the USCS types. At all three sites, this resulted in a uniform type over the area of interest, unlike the VITD soil types as shown in Figs. 1–3. For both Cheorwon and Laboue, the USCS soil type is a CL, while for Asham, it is an SC.

b. Soil moisture

The simulated SMAP L3 soil moisture (L3_SM_A/P) is a daily composite of the merged descending-pass level-2 (L2) active-passive volumetric soil moisture of the top 5 cm (L2_SM_AP). Both data are available on a 9-km EASE fixed grid based on latitude–longitude grid information (Entekhabi et al. 2012). The latency for operational L3 data is 50 h. To generate the L2_SM_AP values, a global-scale simulation (GloSim) for SMAP was implemented on the SMAP SDS. GloSim can generate orbital files of simulated radiometer and radar observations of brightness temperature and backscatter, respectively (Entekhabi et al. 2012). Soil moisture and temperature data from the 9-km Goddard Global Modeling and Assimilation Office (GMAO) Modern-Era Retrospective Analysis for Research and Applications (MERRA) Nature Run data and other 36-km ancillary data [e.g., 17-class Moderate Resolution Imaging Spectroradiometer (MODIS) International Geosphere–Biosphere Programme land cover] are used as underlying truth maps to forward sample observations of brightness temperature and radar backscatter to mimic SMAP-like measurements (Entekhabi et al. 2012). Yi et al. (2011) found that MERRA soil moistures correspond fairly well to both in situ and AMSR-E products in the mid to low latitudes (<50°). We chose the L3 instead of L2 data based strictly on satellite swath position with our areas of interest as determined by terrain data availability. At the time when this study was conducted, simulated SMAP data were available for only one day, making bias corrections extremely difficult. Since the simulated SMAP data are representative of May conditions, we used the soil moisture from the average conditions from the Noah LIS–based climatology, rather than dry, wet, or wet-wet, as discussed in section 1.

The planned 0.04 volumetric soil moisture uncertainty of SMAP may or may not be acceptable for operational mobility applications. Because of the nature of the relationships from soil moisture to soil strength to mobility, the magnitude and importance of change in predicted speed that is caused by a given moisture error will vary based on soil type, moisture range, and vehicle configuration. Currently, a study is underway to propagate errors through the entire process from soil moisture to mobility predictions.

Soil moistures for the Noah LIS–based climatology method were computed according to Baylot et al. (2013) and are described in section 1c of this paper.

c. Soil strength

We followed current practice and used an empirically based equation developed from thousands of in situ measurements taken from around the world to calculate soil strength in terms of either CI [in pounds per square inch (psi), 1 psi = 6895 Pa] for coarse-grained soils or RCI (psi) for fine-grained soils:

\[
CI, RCI = \exp[A_1 A_2 \ln(\theta_w)],
\]

where \(\theta_w\) is the percent soil water content by weight and \(A_1\) and \(A_2\) are constants dependent on USCS soil type and CI, RCI (Sullivan et al. 1997). The curves are plotted in Fig. 4, where it is seen that the change from very strong to very weak happens over a small range of soil moistures. Sullivan et al. (1997) assume that gravels are always at a maximum strength of 300 psi (2068 kPa) for GW and GP and 750 psi (5171 kPa) for GM and GC (Fig. 4). This is due to the fact that Sullivan et al. (1997) treat gravels as compacted unpaved roads. For the purpose of ground vehicle mobility, these can be considered arbitrarily high upper bound soil strengths because few military vehicles are sensitive to RCI values greater than 200 psi (1379 kPa; Corps of Engineers 1956).

We used Eq. (1) to calculate soil strength for the simulated SMAP data as well as the Noah LIS–based climatological soil moistures; we capped all RCI values at 750 psi (5171 kPa). The current method of Baylot et al. (2013) calculates the soil strength based on the Noah LIS HWSD soil type then maps these strengths to the VITD types. For this study, we compare the difference between their method and one where we map the soil moistures to the VITD first, then calculate the strengths. The second approach essentially downscales the soil moistures based on soil texture, assuming that the total soil volume is constant, but the degree of saturation changes according to the new soil type. In both methods, the FASST model default densities (Frankenstein 2014) were used to convert the SMAP and Noah LIS–based climatology volumetric moistures to gravimetric. Although this introduces some error, error is also introduced in converting from USDA soil texture to USCS soil type without other supporting information such as grain size distribution and...
engineering properties like plasticity index and liquid limit.

d. Vehicle mobility

To compare the application of SMAP L3 soil moistures to the current Noah LIS–based climatology method, we will compare the predicted soil strengths and modeled speeds for a single pass of a High Mobility Multipurpose Wheeled Vehicle (HMMWV) M1097 (heavy variant with a hitch). The minimum soil strength, or VCI, needed for this vehicle configuration is 25 psi (172 kPa) for one pass and 58 psi (400 kPa) for 50 passes.

Also as noted previously, we investigate the difference between calculating soil strengths using the Noah LIS–based climatology and simulated SMAP L3 soil moistures and the converted HWSD soil types, and mapping the moistures to the VITD soil types and then calculating the soil strength. The former method was used by Baylot et al. (2013).

HMMWV speeds were modeled for four different terrain scenarios: Noah LIS–based climatology soil moistures using HWSD soil types to calculate soil strength, Noah LIS–based climatology soil moisture using VITD soil types to calculate soil strength, simulated SMAP using HWSD soil types to calculate soil strength, and simulated SMAP using VITD soil types to calculate soil strength. Regardless of which of the four methods was used to calculate soil strength, we used the VITD soil type map to calculate vehicle speeds.

4. Results

a. Soil moisture

The distribution of volumetric soil moistures, as well as the minimum, maximum, average, and median values, at all three sites for both the simulated SMAP and Noah LIS–based climatology calculations are presented in Table 1. The cumulative distribution frequencies (CDFs) for the three sites for both sources of volumetric soil moisture are shown in Fig. 5. The error bars on the simulated SMAP curves represent the 0.04 m$^3$ m$^{-3}$ uncertainty in the final product. The relationship between the volumetric moistures at each site is inconsistent. In Fig. 5, it can be seen that, within this uncertainty, the two sources predict the same distribution at the Nigeria area of interest. At Cheorwon, South Korea, the Noah LIS–based climatology curve is nearly vertical while the simulated SMAP curve is stepped. At the lower volumetric soil moisture values, the two CDF curves are similar. At the Lebanon site, the shapes of the two CDF curves are similar, but they are offset from one another by approximately 0.10 m$^3$ m$^{-3}$, as can be seen in Table 1 and in Fig. 5. In all cases, the simulated SMAP volumetric soil moisture is greater than the Noah LIS–based climatology values, but not by a consistent factor. This is true whether we compare between areas of interest or over the range of volumetric soil moistures at a given site. Unfortunately, no in situ data are available at any of the sites. Given this and the fact that, at the time of this analysis, only one day’s
worth of simulated SMAP data was available, no adjustments were made to either of the volumetric soil moisture sources. Once actual SMAP data are available, bias adjustments in the data must be reinvestigated.

b. Soil strength

The soil strength comparisons for all areas of interest are presented in Tables 2 and 3 for the HWSD and VITD soil type scenarios respectively. At the bottom of both tables are the minimum, maximum, average, and median RCI values. The rest of the rows show the distribution of soil strengths as a function of area. The maximum values for all sites and using both soil type scenarios were well above the RCI value needed for maximum mobility of the simulated HMMWV. As noted in section 3c, the maximum allowed RCI was set to 750 psi (5171 kPa) for all sites. As can be seen in Tables 2 and 3, the soil strength in Nigeria is the maximum value everywhere within the area of interest. That both volumetric soil moisture sources result in the same soil strength is not surprising considering the shapes of their soil moisture CDF curves and the uniformity of the soils for the HWSD and VITD soil types.

At Cheorwon, South Korea, the strengths calculated using both the Noah LIS–based climatology and simulated SMAP volumetric soil moistures and the VITD soil types (Table 3) are in better agreement than those calculated using the HWSD ones (Table 2). As can be seen in the lower portion of Fig. 6, the CDF curves verify this. As with the soil moisture CDF curves, the two strength CDF curves calculated using the simulated SMAP L3 soil moistures are more stepped than the Noah LIS–based climatology ones. For the VITD scenario and both soil moisture sources, 76% of the area has strengths below 100 psi (689 kPa). Above this, the Noah LIS–based climatology soil moistures result in higher strengths than the simulated SMAP ones. Also of note, nearly 3% of the simulated SMAP soil strengths are below the minimum needed by the HMMWV, while only 7% are below the 50 pass strength of 58 psi (400 kPa). Finally, it is evident in Fig. 6 that the Noah LIS–based climatology and simulated SMAP calculated soil strengths are in better agreement if the strengths are calculated after mapping to the finer VITD soil texture grid instead.

As expected based on the volumetric soil moisture CDF curves, the resulting soil strengths at Laboue,
Lebanon, determined using the Noah LIS–based climatology and simulated SMAP data are the most dissimilar of all three of our test sites, as can be seen in Fig. 6. As with Asham, Nigeria, using the HWSD soil types, the Noah LIS–based climatology strengths are uniform and are equal to the maximum of 750 psi (5171 kPa). The simulated SMAP values have a greater distribution, all of which are larger than that needed to support unhindered HMMWV movement (Tables 2, 3).

Mapping the volumetric soil moistures to the VITD soil types before calculating the soil strength resulted in better agreement between the Noah LIS–based climatology and simulated SMAP calculations, similar to our South Korea site. It is not good in either case (Fig. 6). The weakest soils are the SM in the Anti-Lebanon Mountains, while the strongest soils are the highly deformable MH of the Beqa Valley. One thing that is noted, although not shown, is that sometimes abrupt

![Fig. 5. CDF curves of volumetric soil moisture for both the Noah LIS–based climatology and simulated SMAP methods and for all three sites.](image)

**TABLE 2.** Comparison of Noah LIS–based and simulated SMAP area-weighted soil strength distribution using the HWSD soil types. The min, max, avg, and median RCI values are listed at the bottom of the table.

<table>
<thead>
<tr>
<th>Soil strength RCI</th>
<th>Cheorwon, South Korea</th>
<th>Laboue, Lebanon</th>
<th>Asham, Nigeria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Noah LIS (% area)</td>
<td>SMAP (% area)</td>
<td>Noah LIS (% area)</td>
</tr>
<tr>
<td>0–50 psi (0–345 kPa)</td>
<td>0</td>
<td>0</td>
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<td>50–100 psi (345–689 kPa)</td>
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<td>0</td>
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<td>100–150 psi (689–1034 kPa)</td>
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<td>0</td>
</tr>
<tr>
<td>150–200 psi (1034–1379 kPa)</td>
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<td>24</td>
<td>0</td>
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<tr>
<td>650–750 psi (4482–5171 kPa)</td>
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<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Noah LIS [psi (kPa)]</td>
<td>SMAP [psi (kPa)]</td>
<td>Noah LIS [psi (kPa)]</td>
<td>SMAP [psi (kPa)]</td>
</tr>
<tr>
<td>Min</td>
<td>262 (1806)</td>
<td>54 (372)</td>
<td>750 (5171)</td>
</tr>
<tr>
<td>Max</td>
<td>307 (2117)</td>
<td>415 (2861)</td>
<td>750 (5171)</td>
</tr>
<tr>
<td>Avg</td>
<td>276 (1902)</td>
<td>170 (1171)</td>
<td>750 (5171)</td>
</tr>
<tr>
<td>Median</td>
<td>274 (1889)</td>
<td>165 (1138)</td>
<td>750 (5171)</td>
</tr>
</tbody>
</table>
differences in soil moisture are introduced at grid boundaries in the simulated SMAP data. Regardless of whether the strengths are calculated before or after mapping to the finer-resolution VITD soil texture grid, greater variability in strengths is found using the simulated SMAP L3 moistures compared to the Noah LIS–based climatology ones. Also, as was observed at the South Korea area of interest, less variability is found in the two mapping scenarios using the VITD soil textures to calculate strength rather than the HWSD ones.

c. Speed maps

The maximum simulated off-road uphill vehicle speed for the HHMWV is 40 mi h\(^{-1}\) (64 km h\(^{-1}\)). This is achieved at all three areas of interest. The distribution of speeds as a function of area as well as the maximum, average, and median vehicle speeds for the HMMWV M1097 in the uphill direction are presented in Tables 4 and 5 for the HWSD and VITD soil type scenarios, respectively. The uphill rather than the downhill or cross-slope directions was chosen since it is most influenced by soil strength. At all three sites, the main factor affecting vehicle speed is local slope and/or soil strength (≥80%). The secondary factor is vehicle tire limitations.

Even though there are at times large differences between the Noah LIS–based climatology and simulated SMAP calculated soil strengths, especially using the HWSD soil type scenario, the resulting speed maps for the HMMWV M1097 are fairly similar for the three test areas.

This notable improvement in agreement between the two soil moisture sources is especially true for Laboue, Lebanon, as seen in Tables 4 and 5 and Fig. 7. Below 40 km h\(^{-1}\), the distribution of speeds over the test area is the same for the two soil strength mapping methods. Above this, the Noah LIS–based climatology speed distributions are the same, while there is a shift to lower speeds (from 60–70 to 40–50 km h\(^{-1}\)) for the simulated SMAP data between the HWSD and VITD soil texture scenarios, respectively. This behavior is also observed in the CDF curves, as seen in Fig. 7. Regardless of soil moisture source or soil texture mapping, 3% of the area is calculated as “no go.”

In Cheorwon, South Korea, there is a slight difference in speed distributions between the two soil strength mapping scenarios for both soil moisture sources. There is a slightly larger difference in speed distributions for the Noah LIS–based climatology and simulated SMAP L3 moistures, keeping the mapping method constant. A slightly larger percentage of lower velocities are calculated using the simulated SMAP moistures and calculating soil strength using the VITD soil textures (Fig. 7, Table 5). As in Laboue, Lebanon, Cheorwon, South Korea, also has no-go regions for both scenarios. In the VITD scenario, the speeds calculated using the Noah LIS–based climatology volumetric soil moistures result in 5% of the area being no go, while for the simulated SMAP moistures it is 10% (Table 5). For the HWSD scenario, only 2% of the area is no go for both the Noah LIS–based climatology and the simulated SMAP cases, as seen in Table 4.

Unsurprisingly, the smallest difference in soil speeds calculated using the two soil moisture sources is found in differences in soil moisture are introduced at grid boundaries in the simulated SMAP data. Regardless of whether the strengths are calculated before or after mapping to the finer-resolution VITD soil texture grid, greater variability in strengths is found using the simulated SMAP L3 moistures compared to the Noah LIS–based climatology ones. Also, as was observed at the South Korea area of interest, less variability is found in the two mapping scenarios using the VITD soil textures to calculate strength rather than the HWSD ones.

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Unsurprisingly, the smallest difference in soil speeds calculated using the two soil moisture sources is found in

<table>
<thead>
<tr>
<th>Soil strength RCI</th>
<th>Cheorwon, South Korea</th>
<th>Laboue, Lebanon</th>
<th>Asham, Nigeria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Noah LIS (%)</td>
<td>SMAP (%)</td>
<td>Noah LIS (%)</td>
</tr>
<tr>
<td>0–50 psi (0–345 kPa)</td>
<td>0</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td>50–100 psi (345–689 kPa)</td>
<td>76</td>
<td>44</td>
<td>0</td>
</tr>
<tr>
<td>100–150 psi (689–1034 kPa)</td>
<td>0</td>
<td>17</td>
<td>0</td>
</tr>
<tr>
<td>150–200 psi (1034–1379 kPa)</td>
<td>1</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>200–250 psi (1379–1724 kPa)</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>250–350 psi (1724–2413 kPa)</td>
<td>23</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>350–450 psi (2413–3103 kPa)</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>450–550 psi (3103–3792 kPa)</td>
<td>0</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>550–650 psi (3792–4482 kPa)</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>650–750 psi (4482–5171 kPa)</td>
<td>0</td>
<td>0</td>
<td>84</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil strength RCI</th>
<th>Noah LIS [psi (kPa)]</th>
<th>SMAP [psi (kPa)]</th>
<th>Noah LIS [psi (kPa)]</th>
<th>SMAP [psi (kPa)]</th>
<th>Noah LIS [psi (kPa)]</th>
<th>SMAP [psi (kPa)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>83 (572)</td>
<td>22 (152)</td>
<td>386 (2661)</td>
<td>55 (379)</td>
<td>750 (5171)</td>
<td>750 (5171)</td>
</tr>
<tr>
<td>Max</td>
<td>307 (2117)</td>
<td>415 (2861)</td>
<td>750 (5171)</td>
<td>750 (5171)</td>
<td>750 (5171)</td>
<td>750 (5171)</td>
</tr>
<tr>
<td>Avg</td>
<td>135 (930)</td>
<td>79 (547)</td>
<td>710 (4896)</td>
<td>357 (2461)</td>
<td>750 (5171)</td>
<td>750 (5171)</td>
</tr>
<tr>
<td>Median</td>
<td>87 (600)</td>
<td>59 (407)</td>
<td>750 (5171)</td>
<td>142 (979)</td>
<td>750 (5171)</td>
<td>750 (5171)</td>
</tr>
</tbody>
</table>
Asham, Nigeria. Within 1% there is no difference in speed distributions at all speeds (Tables 4, 5). This close agreement can also be seen in the respective CDF curves (Fig. 7). The entire Asham, Nigeria, area allows for unhindered vehicle movement in the moisture conditions used for this study.

5. Conclusions

In this paper, we investigated using simulated SMAP L3 volumetric soil moisture data to calculate soil strength directly and predict vehicle speeds for a HMMWV M1097 instead of the current Noah LIS–based climatology method. Contingent on data availability, three sites were chosen for the study: Cheorwon, South Korea; Laboue, Lebanon; and Asham, Nigeria. Each site represents a different climate zone from humid subtropical to tropical savannah. The simulated SMAP satellite data are representative of May conditions. For all three regions, this best represents “average” soil moisture conditions as defined by climatology.

The current method developed by Baylot et al. (2013), which is predicated on the earlier work of Bullock (1994), converts the agricultural soil types in the HWSD to USCS ones, calculates the soil strength, then maps these strengths to the higher-resolution VITD soil map before calculating the vehicle speeds. We replicate this method with the simulated SMAP L3 soil moistures since it also uses the HWSD soil types to determine the dielectric properties of the soil. For all three areas of interest, this results in a uniform USCS soil type: CL for Laboue, Lebanon, and Cheorwon, South Korea, and SC for Asham, Nigeria. We also test an alternative method. In this approach, we first map the volumetric soil moistures onto the higher-resolution VITD soil map, then calculate the soil strength. The latter method is one approach to downscale the soil moistures to a scale needed by the military for mobility planning purposes.

<table>
<thead>
<tr>
<th>Vehicle speed</th>
<th>Cheorwon, South Korea</th>
<th>Laboue, Lebanon</th>
<th>Asham, Nigeria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Noah LIS (% area)</td>
<td>SMAP (% area)</td>
<td>Noah LIS (% area)</td>
</tr>
<tr>
<td>0 km h⁻¹</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>0–10 km h⁻¹</td>
<td>15</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>10–20 km h⁻¹</td>
<td>40</td>
<td>40</td>
<td>19</td>
</tr>
<tr>
<td>20–30 km h⁻¹</td>
<td>6</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>30–40 km h⁻¹</td>
<td>12</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>40–50 km h⁻¹</td>
<td>9</td>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td>50–60 km h⁻¹</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>60–70 km h⁻¹</td>
<td>15</td>
<td>5</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Noah LIS (km h⁻¹)</th>
<th>SMAP (km h⁻¹)</th>
<th>Noah LIS (km h⁻¹)</th>
<th>SMAP (km h⁻¹)</th>
<th>Noah LIS (km h⁻¹)</th>
<th>SMAP (km h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Max</td>
<td>64</td>
<td>64</td>
<td>64</td>
<td>64</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>Avg</td>
<td>28</td>
<td>25</td>
<td>38</td>
<td>35</td>
<td>55</td>
<td>56</td>
</tr>
<tr>
<td>Median</td>
<td>20</td>
<td>18</td>
<td>34</td>
<td>33</td>
<td>64</td>
<td>64</td>
</tr>
</tbody>
</table>

FIG. 6. CDF curves of soil strength (RCI) for both the Noah LIS–based climatology and simulated SMAP methods: (top) Laboue, Lebanon and (bottom) Cheorwon, South Korea.
In section 4, we refer to these two scenarios as the HWSD and VITD methods, respectively. Regardless of when the soil strengths are calculated, volumetric soil moistures were converted to gravimetric ones using the default soil properties found in the FASST model (Frankenstein 2014).

The CDF curves of soil moisture indicate mixed agreement between the two volumetric soil moisture sources. Within the 0.04 m$^3$ m$^{-3}$ anticipated uncertainty in the SMAP L3 moisture product, the Noah LIS–based climatology and simulated SMAP L3 soil moisture CDF curves are in agreement at Asham, Nigeria. At Cheorwon,
South Korea, there is agreement in the two curves at the lower soil moistures, but they diverge as moisture increases. Although the shapes of the CDF curves are similar at Laboue, Lebanon, the two curves are offset by 0.10 m$^3$ m$^{-3}$. Because of the fact that the relationship between the CDF curves for the Noah LIS–based climatology and simulated SMAP L3 volumetric moistures are inconsistent and also that there was only one day's worth of simulated SMAP data available at the time of this study, we did not adjust either of the datasets.

Except for Asham, Nigeria, where no difference is found between the HWSD and VITD scenarios, better agreement is found in soil strengths at the other two sites using the VITD method, that is, mapping the soil moistures to the finer-resolution soil type map and then calculating the soil strength, rather than calculating soil strength first and then performing the mapping. At both Cheorwon, South Korea, and Laboue, Lebanon, the soil moisture CDF curves are dissimilar, although less so for Cheorwon. As can be seen in Table 1, the distribution of volumetric soil moistures is narrower for the Noah LIS–based climatology than for the simulated SMAP data. At Laboue, Lebanon, they are also considerably drier. When using the HWSD method, the resulting soil strengths at the Lebanon site are equal; in South Korea there is some variation, but only about one-tenth of that seen with the simulated SMAP soil strengths. One feature that is apparent in all three areas is the need to smooth values across SMAP grid boundaries to eliminate unnatural discontinuities in soil moisture and hence soil strength.

For this study, we confined the dependence of vehicle speed calculations to only soil strength, vehicle tire limitations, and soil slope. At each site, the CDF curve of speeds resulting from the two soil moisture sources and the two mapping methods are essentially the same. The disparities in soil moisture and soil strength could lead to the expectation of large differences in vehicle speed. However, the results demonstrate that the key differences in soil moisture are those that affect the region of soil strength to which the vehicle is most sensitive [in this case, RCI of approximately 0–58 psi (0–400 kPa)]. Further investigation into the sensitivity of modeled vehicle speeds to soil moisture is clearly necessary.

A separate study is underway to investigate the result of uncertainty in the various factors influencing vehicle speed, including soil moisture. Errors resulting from 0.04 m$^3$ m$^{-3}$ SMAP L3 volumetric soil moisture measurement accuracy as well as measurement bias will be quantified at this time. It is expected to have the greatest effect at low soil strengths where vehicle mobility is most sensitive to soil strength. The sensitivity seems to be only partly from the moisture to strength curve but mostly from the strength to mobility curve, which varies from one vehicle to the next.

At the time of this study, the SMAP data were simulated and available for only a short period of time, making long-term climatological studies or true data assimilation impractical, if not impossible. Direct, autonomous measurements of soil strength are more desirable but are still very much at the research level. Thus, empirical equations are used to relate strength to moisture based on soil type. There is much scatter in the data because of large differences in soil properties within a given texture class, as well as errors associated with large- and small-scale moisture measurement. Therefore, until remote measurements of strength are available, the best way to improve this aspect of mobility predictions is through better soil moisture estimates.

We have shown in this paper that soil strength generated using simulated remotely sensed measurements of soil moisture can be used for mobility modeling. Realistic patterns of soil strength and vehicle speeds were generated. It is recommended that soil strength is calculated after mapping the larger-scale soil moistures to a finer scale rather than before.

This was a feasibility study. A follow-on to this study must include comparison with field measurements. Also, we only tested the trafficability of one vehicle, the HMMWV M1097. More vehicles, both tracked and wheeled, need to be investigated before further conclusions can be made. The U.S. Air Force has been providing soil moisture analysis products for agricultural purposes for many years. Since the development of LIS, it has been using this environment, complete with its terrain geostatistics and ground vehicle mobility predictions.

It has been shown that soil strength generated using simulated remotely sensed measurements of soil moisture can be used for mobility modeling. Realistic patterns of soil strength and vehicle speeds were generated. It is recommended that soil strength is calculated after mapping the larger-scale soil moistures to a finer scale rather than before.

Acknowledgments. This study was funded by the Army 6.2 applied research program GeoEnabled Multi-Modal Situation Awareness–Targets and Terrain Simulation (GEMS-T2S). Recognition also goes to the SMAP Early Adopter Program.

REFERENCES


