Full Length Article

Strata: Mapping climate, environmental and security vulnerability hotspots

Hannah R. Young a,1, YoungHwa Cha a, Hannah den Boer b, Marie Schellens c, Kathryn Nash b, Gary R. Watmough a,d, Kate Donovan a,e, Genevieve Patenaude a,f, Sam Fleming f, Ben Butchart f, Iain H. Woodhouse a,1

a School of GeoSciences, University of Edinburgh, Drummond Street, Edinburgh, EH8 9XP, UK
b Edinburgh Law School, University of Edinburgh, Old College, South Bridge, Edinburgh, EH8 9YL, UK
c Disasters and Conflicts Branch, United Nations Environment Programme, Chemin des Anémones 15, 1219, Vernier, Switzerland
d Global Academy of Agriculture and Food Systems, University of Edinburgh, Easter Bush Campus, Bush Farm Road, Edinburgh, EH25 9RG, UK
e Edinburgh Climate Change Institute, University of Edinburgh, High School Yards, Infirmary Street, Edinburgh, EH1 1LZ, UK
f Earth Blox, 6 Redheughs Rigg, Edinburgh, EH12 9DQ, UK

ARTICLE INFO

Keywords:
Climate hazard
Environmental change
Conflict
Vulnerability
Exposure
Google Earth Engine

ABSTRACT

Climate and environmental changes, as well as conflict events and violence, can have compounding impacts on livelihoods and the safety and security of population groups, particularly when multiple events are interrelated, coincide or occur in succession. How people are impacted depends on where they are located, how vulnerable they are, and the magnitude of the hazard. Although a significant amount of geospatial data is freely available, there has been a lack of user-friendly data tools allowing for integrated data-driven assessments of these complex climate-related security risks. Strata is such a tool, developed by a multidisciplinary team and co-designed with practitioners in the fields of peacebuilding, climate adaptation and environmental conservation. It addresses the need for making visible the available climate and conflict data via a web browser and allows a high level of analysis and customisation by users. Here we describe the process of co-developing the principles behind Strata and pathways for continued development of the tool. We also highlight how user insights can be incorporated in this and similar tools, to ensure actionable data-driven insights within the context of available data and understandings of impact pathways.

1. Introduction

Environmental changes, extreme weather events, climate change, societal unrest and violent conflicts are all stresses that can have large impacts on livelihoods and the safety and security of populations. These, often interrelated, impacts can be particularly severe when multiple events occur at the same time (e.g. Anderson et al., 2021; Leonard et al., 2014) or in succession (e.g. Haile et al., 2019; Lwanga-Ntale & Owino, 2020). How such events impact people and contribute to risk depends not just on the stresses (also called hazards) occurring but also on the exposure, capacity and vulnerability of populations (Lavell et al., 2012). Therefore, to manage and reduce the impacts of events it is necessary to understand both where people are located relative to stresses and who is most vulnerable.

As the scientific understanding of climate-related security risks has steadily increased over the past two decades (von Uexkull & Buhaug, 2021), the demand has grown for more and improved science-based decision-making, project design and implementation (Council of the European Union, 2020; United Nations, 2021). If decision-makers and field practitioners are to be able to use information about stresses, exposure and vulnerability, it needs to be accessible in tools which do not require prior technical expertise or vast amounts of training to use. Co-designing such tools with users can ensure this is achieved and that outputs are easy to interpret and apply to decisions and projects. Tools should also be customisable, providing users with options to specify what data is used, how it is converted to outputs, and the temporal and spatial scale of data aggregation.
spatial extent of the analysis, so users can access the information they require for their specific context.

Data is required at different timescales, depending on the decisions being considered, from historical information to current monitoring and future projections. Online data repositories such as Google’s Earth Engine offer access to petabytes of geospatial data across more than 700 datasets (Gorelick et al., 2017; Ilyushchenko et al., 2020), many of which are pertinent to the topics of environmental and climate-related stresses, human exposure and socioeconomic vulnerability. Unfortunately, to use Earth Engine requires coding skills and knowledge of what to do with the data. Tools that help users access and analyse this data without requiring coding expertise, or satellite data processing skills, are therefore required to support the decision makers who could take advantage of such data. In addition, it may be particularly useful for tools to allow users to aggregate data and view information from multiple data sources at once. This would allow users addressing the impacts of multiple types of environmental and security challenges to identify where stresses and vulnerabilities converge in space and time. Enabling an understanding of the various risks and possibilities for response across disciplines is essential (Holland & Tye, 2016; Hughes & Rees, 2016; Kappes et al., 2012), especially for those working in climate security.

With this background in mind, the United Nations Environment Programme (UNEP), in collaboration with the University of Edinburgh and Earth Blox, developed Strata as a web tool to provide user-friendly access to data and provide an aggregation framework to identify and monitor climate and security risks. Strata is aimed at two main user groups: (1) environmental practitioners and policy-makers looking to deliver conflict-sensitive climate and environmental programming in conflict-affected and fragile regions; and (2) political analysts and peace and security practitioners looking to deliver climate-sensitive conflict prevention and peacebuilding initiatives. Strata adopts a “hotspot” approach to provide information regarding where environmental, climate, and peace and security stresses overlap with exposed and vulnerable populations. In so doing, it aims to support decision-makers in addressing potential impacts. These areas where multiple stresses overlap with high levels of exposure and vulnerability are referred to as “hotspots” in Strata. The focus is on using available geospatial data to monitor the current situation using as up-to-date information as is available, and with a key focus on incorporating satellite information, rather than to develop a predictive early warning tool. It provides “situational awareness” rather than being “predictive”.

Our approach also aims to ensure a customisable user platform so that users can tailor the hotspot analysis to their local context of interest. The web platform itself has been developed by Earth Blox who specialise in producing tools that allow no-code access to insights from satellite and geospatial data. Strata has initially been developed for Somalia as a pilot study, with plans to scale to other regions.

In this paper we describe the theoretical background behind Strata and its method for aggregating stresses with exposure and vulnerability. We demonstrate example results provided by the platform and reflect on the co-design process with users and ongoing development plans.

In section 2 we describe how hotspot mapping approaches have been used in other tools and what lessons Strata takes from these. Section 3 provides detailed descriptions of the co-design approach, hotspot framework and calculations, indicators and datasets. A discussion of the types of results produced by the Strata platform are in Section 4, and section 5 reflects on challenges in co-designing such a tool, how to interpret the results and how the Strata platform will continue to develop. Conclusions are in Section 6.

2. Climate, security and vulnerability hotspot mapping tools

Hotspot mapping has often been used to identify locations that are particularly vulnerable to climate, environmental or security impacts. The maps often display an index aggregating information across multiple datasets characterising the stresses and vulnerabilities of interest (de Sherbinin, 2014). Various approaches have been used to create the aggregated indices. Busby et al. (2014) assessed climate security vulnerability across Africa using a summation approach to show how many indicators had passed a threshold, across measures of resilience, population, climate hazards, and governance and political violence. Ide et al. (2014) assessed where high exposure and vulnerability to climate change and a high risk of violent conflict were most likely to co-occur across Kenya and Uganda. The indicator data was also summed but, instead of using thresholds, grid cells across the region were ranked into quantiles. Midgley et al. (2011) also used a summation approach to combine climate exposure, sensitivity and adaptive capacity data layers to map climate risk and vulnerability hotspots in Southern Africa. These approaches can result in outputs that are relatively simple to interpret. However, they can lead to areas being flagged as a hotspot even when no climate hazards are flagged, or where very small populations are located (Busby et al., 2014). This may be misleading when the hotspots are framed as locations where decision makers should direct their attention because climate impacts are expected to be greatest, but there is no climate hazard or a very low population.

Thornton et al. (2006) applied principal component analysis to determine the most important indicators characterizing vulnerability to climate change in Africa. While this avoids correlations between indicators, the new indicators are independent combinations of the original set and are not easily interpretable by users (Thornton et al., 2006). Kok et al. (2016) used cluster analysis to identify patterns in vulnerability data and locations with similar vulnerability profiles. This can help policymakers to identify which regions are in similar situations and where successful policy interventions may be transferable (Kok et al., 2016). However, this approach can be very computationally intensive, which potentially makes it less suitable for a customisable online tool that may need to be updated regularly.

There already exist several online mapping tools designed to monitor multidimensional sets of climate and environmental-related risks at scale. These risks include food insecurity (Famine Early Warning System Network (FEWSNET)), water risks (Aqueduct), reductions in agricultural production (Anomaly Hotspots of Agricultural Production (ASAP)), drought (Global Drought Observatory). Some mapping tools focus on certain countries or regions, providing data particularly relevant to that location, such as the Food Security and Nutrition Analysis Unit – Somalia (FSNAU) Early Warning Early Action Dashboard and the East Africa Hazards Watch tool. A more global perspective covering a range of environmental risks is provided by MapX (Lacroix et al., 2019) and Resource Watch. Focusing specifically on climate security, the Strauss Center’s Climate Change and African Political Stability (CCAPS) mapping tool was designed to visualize climate security risks across Africa from 1990 to 2016. Additionally, the visual explainer ‘How Climate Change Fuels
Deadly Conflict provides a snapshot (as of 2021) of current and future climate risk and conflict globally, as well as more detailed case studies in Africa.

These existing tools demonstrate a number of features which we have taken forward into the development of Strata, including the ability to view and overlay different map layers, enabling comparisons over different time periods, and providing personalised dashboards with summary information for a country or specific issue. These tools also highlight the importance of clearly showing how data feeds into aggregated indices. However, a key limitation of each of these existing tools is that they do not offer much scope for users to interactively customise the inputs, thresholds, or outputs in the calculations. Tailoring analyses to local historical, political, cultural and environmental contexts and conditions is critical for practitioners in the climate and environmental security field, as they have the expert understanding of the interactions between stresses and how these impact people and their security in each locality. Strata therefore not only addresses the needs of analysts and project managers in the climate and environmental security fields by providing near-real time climate security data analysis, not available elsewhere, but provides this with a customisable approach where users can interact with and modify the analysis. Additionally, Strata improves on how population exposure and socioeconomic vulnerability are accounted for in hotspots alongside information on stresses.

In a review of global climate change hotspot mapping approaches, de Sherbinin (2014) noted that while many hotspot maps were produced with the goal of being used by policy audiences, they tended to lack a specific audience and were not developed in response to particular needs from policymakers. Conversely, Strata has been developed in response to demand from, and in collaboration with, climate security practitioners at a specific international organisation (UNEP). Further, the team consulted with a broad audience of stakeholders related to environmental and climate risk monitoring (89 stakeholders from 48 organisations during 2020), leading to a focus on practitioners working on the nexus of peacebuilding, environmental restoration, and climate adaptation as the main targeted users. Most importantly, Strata was co-designed with those practitioners to ensure the information provided is relevant to the decisions they need to make (further detail on the co-design process is in Section 3.1).

3. Methods

3.1. Case study and Co-design approach

To ensure a strong user-centric co-design approach and develop Strata as a relevant tool for decision support from local to regional scale, only a small number of countries were considered for the first version. Consultations included participants from Somalia, Haiti and Colombia. To develop the platform itself, Somalia was chosen because of (1) its long history of experiencing climate-related security stresses including drought, floods, food insecurity, intercommunal and political conflict, and terrorism, as well as a highly vulnerable population (Funk, 2020; Human Rights Watch, 2021; Maxwell & Fitzpatrick, 2012; Maystadt & Ecker, 2014; UNDP, 2012; UNDP, 2018); (2) its limited accessibility for field data gathering and thus its dependency on remote sensing; (3) yet easy communication with stakeholders and potential users in international organisations and civil society organisations through UNEP’s advisor to the United Nations Assistance Mission in Somalia (UNSOM).

Co-design with end-users can ensure tools are able to support decision-making, increasing user productivity and satisfaction (Trischler et al., 2019). Strata adopted such an approach to ensure the tool is informed by end-users’ needs and, in particular, incorporates their feedback on the framework, indicators and datasets used. The Strata co-design process (summarised in Fig. 1) included an initial survey and follow up semi-structured interviews identifying what such a platform needed to include and what types of decisions are typically made that could use the support of spatial data (March–April 2021). This was followed by five co-design workshops to collect input and feedback on the design and content of the platform, the choice of method and the user interface (May–June 2021). Later workshops provided a demonstration and hands-on testing of the platform to collect feedback on its usability and outputs shown to inform further development (October 2021). Potential users of the platform involved in this process included representatives from UN organisations, NGOs and research organisations (a full list of organisations represented is in Appendix A, along with a selection of representative quotes from the surveys, interviews and workshops).

While this means that the indicators selected for initial inclusion in Strata were of particular relevance to Somalia, the development of the platform and the approach taken were designed to allow for simple extension to other countries and regions. The co-design process included potential users working in countries other than Somalia, to ensure that the framework developed would be relevant to other regions. The risk and aggregation frameworks are generally applicable from local to global scales and the indicators developed for Somalia were, as much as possible, based on timely geospatial datasets available for most parts of the world.

3.2. Risk and hotspot framework

The Convergence of Evidence approach (Cherlet et al., 2018; United Nations Convention to Combat Desertification, 2017) was developed to identify locations where land degradation might be occurring, based on where indicators relevant to land degradation coincide. In this approach, the output is a simple summation of the number of indicators that cross some pre-defined critical thresholds. Areas of concern are those locations where the most thresholds have been crossed. We adopted a similar approach for Strata. Strata’s scoring framework is based on the summation of “red flags” that occur wherever climate, environmental, or security indicators cross pre-determined thresholds (we define an “indicator” to be a quantitative or qualitative geotagged dataset used to monitor these natural or socioeconomic characteristics, based on one, or a combination of, data layers. The indicators and their thresholds are described in section 3.3). This creates a map of aggregated stress based on the indicators chosen. The aggregated stress map can then be scaled to account for population exposure and socioeconomic vulnerability, scaling the number of flags according to the relative exposure and vulnerability of the population compared to the rest of the country of interest (Fig. 2). In this way Strata’s hotspot framework is based on the Intergovernmental Panel on Climate Change’s conceptualisation of risk as the combination of hazard (here called stress), exposure and vulnerability (Lavell et al., 2012). The calculations for the exposure and vulnerability scores are described in section 3.4, and these scores are optional inclusions in the hotspot maps.

The scoring ensures that a location will have at least one climate, environmental or security stress in order to be flagged, but the likely impact of the stress(es) will be scaled according to population exposure and socioeconomic vulnerability (where reliable data is available). This addresses issues raised by Busby et al. (2014) who used a purely additive approach which led to locations being identified as climate security vulnerability hotspots despite having very low populations or having very low climate-related risk. The Strata framework implicitly assumes that a location with more red flags is an area of greater concern than an area with fewer flags. One of the key reasons for choosing this scoring approach was to emphasise that Strata is not designed as a predictive modelling tool. It does not present an unambiguously modelled quantitative index of risk, but rather is merely aggregating relevant indicators from disparate data sources to draw attention to areas where multiple stresses are co-occurring. Strata does not weight across different stresses,
nor does it accommodate non-linear interdependencies between stresses, so hotspots are perhaps best considered as “areas of concern” rather than “areas of higher risk.” This does not exclude the possibility that hotspots are indeed areas of higher risk, but we caution against making inferences or quantitative comparisons between hotspots that may be driven by different indicators. Our ambition is that users will use the dashboard output to interrogate the hotspots so that they can see what is causing high scores. Their own knowledge and understanding of the context then allows them to interpret the hotspot in a more locally framed way.

This transparent approach also allows users to account for the non-linear effects of risk themselves. The cascading effects of climate change on social and political realities, including, for example, relationships between climate change, natural resources, and various levels of human insecurity (including violent conflict) are an important area of discussion (e.g. Gleditsch, 2021; von Uexkull and Buhaug, 2021). In particular, while climate may have an impact on conflict risk, there is low confidence in how this might occur, and other drivers are perceived to have much greater influences (Mach et al., 2019). Consequently due to limited generalizable principles in this area (Mach & Kraan, 2021), Strata focusses merely on identifying where indicators reach relevant thresholds rather than implying pathways between drivers and impacts.

3.3. Indicators

Strata categorizes its indicators into four “baskets” (collections of

Fig. 1. Strata’s co-design process: the series of surveys, interviews and workshops with the goal of each activity and the number of participants involved. (Many participants attended more than one activity and so the total number of participants is less than the sum across the activities.)

Fig. 2. Hotspot calculation used in Strata. The accumulation of “stressors” is additive, whereas accommodating for population exposure and socioeconomic vulnerability is multiplicative, scaling the hotspots. Exposure and vulnerability scores are both optional inclusions.
similar indicators): (1) Climate and environmental stress; (2) Peace and security; (3) Population exposure and (4) Socioeconomic vulnerability. The indicator selection process included reviewing scientific literature for relevant stresses and vulnerabilities in Somalia (as the test case country), identifying existing indicators used in other similar studies, and carrying out a survey and semi-structured interviews with end-users. This process generated a long list of indicators that were then prioritized during co-design workshops with end users. Indicators were also compared to data available in Google Earth Engine (Gorelick et al., 2017), and other online data repositories, to determine where datasets with frequent and automatic updates were available with options for simple and fast uploading into Strata. We particularly focused on using satellite datasets with high spatial and temporal granularity. Table 1 shows the final indicators selected across the three baskets in this first version of Strata. Further detail of the datasets and variables used, thresholds applied, and spatial and temporal availability of the data are provided in Appendix B.

Key indicators included in the prototype version of Strata to characterize climate and environmental stresses were drought (both meteorological and agricultural14), floods, heatwaves, sea level rise, deforestation and land degradation. Where possible, datasets were selected to allow up-to-date monitoring of conditions (e.g. daily rainfall estimates for monitoring meteorological drought). However, where this data was not available, modelled probabilities of events were used instead of observations (e.g. flood likelihood).

The peace and security indicators identify where past violent events and demonstrations have occurred to highlight fragile localities. We are aware that the state of peace and security is contingent on a great many other variables, such as underlying tensions, societal or institutional resilience, and external influences. However, the current lack and limitations of subnational, geotagged data and proxies for peace and security conditions restrict us from portraying a more accurate picture. Data and event categorization is taken from the Armed Conflict Location & Event Data Project (ACLED; Raleigh et al., 2010), as it records the widest range of violent events and demonstrations due to its low threshold for data inclusion, compared to other conflict datasets. Most other datasets have fatality thresholds (e.g. 25 battle-related deaths or more) or thresholds around themes of violent events (e.g. civil wars), which means they leave out various types of unrest and violence that do not meet their particular threshold. ACLED namely also captures non-violent unrest such as protests (these can indicate junctures or precursors in periods of disorder (ACLED, 2021)), and since ACLED has no fatality threshold, we can include conflict events in Strata throughout its categories even if no fatalities have been recorded. In accordance with ACLED’s conflict event types, Strata events include battles, explosions/remote violence, violence against civilians, protests, and riots.

The population exposure and socioeconomic vulnerability indicators provide relative comparisons across the region of interest. Exposure is currently considered in terms of the total population. Vulnerability indicators provide a broad selection of possible drivers of vulnerability to climate, environmental, peace and security stresses, rather than focusing on vulnerability relative to particular types of stress. This ensures the hotspot calculations can be applied to a wide range of stresses. However, users are also able to include or exclude indicators according to their understanding of what is most important in each context. The role of socioeconomic factors in driving vulnerability to climate and environmental changes is well-recognized, as a lack of ability to access resources, power relations, and poverty place more strain on coping behavior (Adger, 2006). However, socioeconomic aspects of vulnerability can be difficult to measure, with data often unavailable at relevant spatial scales which necessitates the development and use of proxies (de Sherbinin, 2014). In particular, as there can be large variations in

### Table 1
Indicators used in Strata, categorized into baskets. Note that users can modify thresholds and directionality for each indicator as appropriate.

<table>
<thead>
<tr>
<th>Basket</th>
<th>Indicator</th>
<th>Data Source</th>
<th>Default assumed directionality (relationship with hotspot score, i.e. what will flag a stress or increase the exposure/vulnerability scores?)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental and Climate Stress</td>
<td>Drought (meteorological)</td>
<td>CHIRPS precipitation (Funk et al., 2015)</td>
<td>Low rainfall index</td>
</tr>
<tr>
<td></td>
<td>Drought (agricultural)</td>
<td>MODIS/Terra NDVI (Didan, 2015)</td>
<td>Low vegetation index</td>
</tr>
<tr>
<td></td>
<td>Heatwave</td>
<td>ERAS-Land temperature (Muñoz Sabater, 2019)</td>
<td>High temperature</td>
</tr>
<tr>
<td></td>
<td>Flood likelihood</td>
<td>WRI Aqueduct Flood Hazard (Ward et al., 2020)</td>
<td>High flood likelihood</td>
</tr>
<tr>
<td></td>
<td>Coastal inundation</td>
<td>SRTM Digital Elevation Data (Farr et al., 2007)</td>
<td>Low height above sea level</td>
</tr>
<tr>
<td></td>
<td>Deforestation</td>
<td>Hansen Global Forest Change (Hansen et al., 2013)</td>
<td>High deforestation rate</td>
</tr>
<tr>
<td></td>
<td>Land degradation</td>
<td>SDG Indicator 15.3.1 Land degradation (Conservation International, 2018)</td>
<td>High levels of degradation</td>
</tr>
<tr>
<td>Peace and Security</td>
<td>Violence against civilians</td>
<td>ACLED (Raleigh et al., 2010)</td>
<td>Recent event</td>
</tr>
<tr>
<td></td>
<td>Remote violence/explosions</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Protests</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Riots</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Battles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Population exposure</td>
<td>Exposed population</td>
<td>WorldPop Global Project Population Data (Linares et al., 2012)</td>
<td>High population</td>
</tr>
<tr>
<td>Socioeconomic vulnerability</td>
<td>Elderly (proportion of population)</td>
<td>WorldPop</td>
<td>High proportion</td>
</tr>
<tr>
<td></td>
<td>Children (proportion of population)</td>
<td>WorldPop</td>
<td>High proportion</td>
</tr>
<tr>
<td></td>
<td>Female (proportion of population)</td>
<td>WorldPop</td>
<td>High proportion</td>
</tr>
<tr>
<td></td>
<td>Urban expansion (increasing population density in urban areas)</td>
<td>WorldPop and ESA WorldCover (Zanaga et al., 2021)</td>
<td>High population growth</td>
</tr>
<tr>
<td></td>
<td>Population growth</td>
<td>WorldPop</td>
<td>High population growth</td>
</tr>
<tr>
<td></td>
<td>Night-time light intensity decline</td>
<td>VIIRS Nighttime Day/Night Band Composites (Elvidge et al., 2017)</td>
<td>Low night-time light intensity</td>
</tr>
<tr>
<td></td>
<td>Displacement</td>
<td>International Organization for Migration (The Malaria Atlas Project)</td>
<td>High number of displaced people</td>
</tr>
<tr>
<td></td>
<td>Travel time to urban areas</td>
<td>Accessibility to Cities 2015 (Weiss et al., 2018)</td>
<td>High travel time</td>
</tr>
</tbody>
</table>

---

14 Meteorological drought refers to a reduction in rainfall, whereas agricultural drought refers to impacts on crops due to reduced moisture availability.
households’ vulnerability, data is required at higher spatial resolutions than national level (Thornton et al., 2006). While studies often use household surveys to capture sub-national variation in vulnerability (e.g. Okpara et al., 2017), these can lack wide geographic coverage, are not available on a regular basis, are rarely available in conflict-affected regions, and are often derived using different methods making cross comparisons difficult. Therefore, Strata makes use of pre-existing socio-economic datasets with high spatial resolution and global coverage (such as population age distributions and travel times to urban areas) where possible, and includes proxy indicators to represent socio-economic factors not otherwise directly measurable.

### 3.4. Thresholds, and exposure and vulnerability scores

The thresholds that determine if an indicator is classed as a red flag or not are a key component of hotspot scoring. Strata provides default thresholds for each indicator, however users can also adapt thresholds according to their context and based on their understanding of the conditions under which they might anticipate different impacts. Fig. 3 shows Strata’s user interface, including options for selecting indicators and adjusting thresholds. For example, thresholds might be changed during different times of the year (e.g. dry vs wet season), during certain events (e.g. an election), for different countries or locations within a country, or for different impacts (e.g. thresholds relevant for different crops). Appendix B provides details of default thresholds for each indicator.

The type of threshold used varies according to the different types of indicators and data available, and for some indicators multiple types of thresholds could be used. These can be broadly categorized into:

- **Absolute thresholds.** For some indicators there is a fixed value set as a threshold which determines when particular stresses might be experienced; this value is fixed across all locations. This is relevant where there are thresholds related to specific impacts, or where fixed thresholds have been chosen based on literature. Examples include temperature thresholds for heatwaves, land height above sea level for coastal inundation, or the number of protest event days within the past year.

- **Thresholds relative to past conditions.** For many indicators, the threshold is set to flag conditions that are significantly different than
the historical conditions. This approach usually flags occurrences that are outside a percentile range based on historical data for the location. These thresholds ensure that the actual value of the threshold varies according to the bio-climatic conditions in each location, rather than being set across a large area average. Examples include thresholds applied to the vegetation index to determine drought as low vegetation conditions compared to normal, or flagging deforestation rates that are higher than usual for the location. These can be calculated with a high degree of spatial granularity, as defined by the input data. The capacity of Strata to calculate the historical trends for given locations and times is one of its important differentiating features.

**Thresholds relative to other locations.** In cases where indicator data is only available at one point in time, or is updated very infrequently, thresholds are set to flag the locations with the values corresponding to highest level of stress or vulnerability across the country at that time, therefore flagging locations that are significantly more at risk than other locations (at the time the data is valid for). This approach usually flags locations where data is more than a particular number of standard deviations from the mean across the whole area. Examples include population density and travel time to urban areas, which each flag locations more than one standard deviation above the mean calculated across the whole country.

To account for the population exposed to climate and environmental stresses and peace and security stresses, we incorporated an exposure score (see Fig. 2). The calculation of the exposure score does not have a threshold associated with it. Instead, we adopt a comparative scale to identify the range of exposure within the country. The population data (number of people per grid cell) undergoes log-transformation and is then scaled across the area of interest from 0 to 1, i.e. from lowest to highest population, and therefore least-to-most exposed areas. The socioeconomic vulnerability score is based on several indicators, each with their own threshold. As socioeconomic data is often unavailable with a historical time series, temporal comparison is often not possible to determine which areas are more vulnerable than they have been previously. We therefore focus on identifying which areas are the most vulnerable within the country, based on the most recent available data for each indicator, taking the “thresholds relative to other locations” approach described above. The overall socioeconomic vulnerability score between 0 and 1 is calculated as

\[
\text{Vulnerability score} = \frac{\text{number of vulnerability flags a location receives} + 1}{\text{total number of vulnerability indicators} + 1}
\]

The higher scores represent the more vulnerable areas in the country. While users can modify the threshold applied to each indicator, as well as choose which indicators to include, they cannot change the weightings associated with the indicators. Weightings affect how much each indicator contributes to an overall score. Midgley et al. (2011) weighted indicators according to importance, confidence in accuracy, or spatial resolution. However, in Strata by default all indicators are equally weighted. This is chosen as the simplest approach to allow users to interpret the resulting Strata scores, to more easily allow for selecting and deselecting specific indicators, and to avoid any over-fitting. Over-fitting may be possible if one can change both the thresholds and the weightings, and some users could use this to apply bias to their analysis.

For such thresholds the data is converted to the z-score, \( Z = (x - \mu)/\sigma \), where \( x \) is the original value, and \( \mu \) and \( \sigma \) are the mean and standard deviation across the area of interest. This score converts the data to the number of standard deviations from the mean, and so a threshold of \( z \)-scores above 1 would flag data points more than one standard deviation above the mean for the area.

4. Hotspot maps for Somalia

4.1. Hotspot maps of the components of the Strata score

Fig. 4 shows maps separated out into the four baskets: Climate and environmental stress, Peace and security, Population exposure and Socioeconomic vulnerability. These include all the indicators in Table 1 with their default thresholds applied, calculated for the period October–December 2016, the second rainy season of the year in Somalia (Deyr). In 2016 the Deyr season was reported to have failed, following poor rains in the first rainy season of the year (FEWS NET, 2017a). Correspondingly, the Climate and environmental stresses basket shows high values across much of the country indicating multiple indicators have passed thresholds. In particular, the drought indicators are flagged across large areas of the country (not shown here but users can view on the dashboard which of the particular indicators are flagged). The Peace and security basket shows many flags in the area broadly around Mogadishu and following the main roads in and out of this area. Population exposure is highest in and around Mogadishu as well as in the far north, while the Socioeconomic vulnerability score is highest around Mogadishu and central parts of Somalia.

4.2. Hotspot maps of the overall Strata score

Fig. 5 shows the hotspot maps for the overall Strata score: summing Climate and environmental and Peace and security stresses, and applying both the exposure and vulnerability scores, for the indicators as in Fig. 4 (i.e. all indicators in Table 1 with default thresholds applied). Users can choose whether or not to include the exposure and vulnerability scores in the hotspot maps. Users can also choose to view results as the raw score for each pixel (Fig. 5a), or with a heatmap applied (based on Gaussian kernels) to smooth out the data and emphasise that stresses in one pixel are likely to have impacts in neighbouring areas (Fig. 5b). The maps indicate that highest scores are located mainly in the area surrounding Mogadishu, with lower magnitude hotspots in other major settlements. Fig. 5c shows the same data but aggregated to the district level. Users can view the output data at pixel scale, regional, and district levels on the Strata dashboard, as well as in tables and charts. Data is aggregated to the larger spatial scales by averaging the hotspot scores at pixel level across the area of interest. Where indicator thresholds are selected relative to the whole country, this is still calculated at a pixel scale, before aggregating the results. The highest score here is in the district of Banadir, where Mogadishu is located, with relatively high scores in the surrounding districts and further south in Jamaame, but lower scores elsewhere.

The district map helps quickly identify areas experiencing greatest levels of stress, exposure and vulnerability. The pixel and heatmaps allow users to investigate where smaller scale stresses are located, which may not show up when averaged to larger spatial scales. For example, the hotspots around cities, where there are fewer stresses flagged than around Mogadishu, still have relatively high and vulnerable populations meaning these areas show up as hotspots on the higher spatial resolution maps.

4.3. Climate security risk in Somalia

Strata’s maps for October–December 2016 show climate and environmental stresses across the country, but overall hotspots mainly around the Mogadishu area as this is where the climate and environmental stresses converge with past conflict events and a very high exposed and relatively vulnerable population. Elsewhere in Somalia the hotspot scores are generally lower. While parts of central Somalia to the north of Mogadishu are highly flagged for climate and environmental stresses, when combined with low peace and security flags and a relatively low population (despite having a high vulnerability score), this
does not show as a hotspot when all indicators are taken into account. This shows how the hotspots highlight both where there are multiple stresses occurring but importantly also where exposed and potentially vulnerable populations are located relative to those stresses. However, the flexibility of the indicator framework means the user still has the option to exclude the exposure or vulnerability scores from the hotspots if they just want to focus on where the stresses are occurring.

In reality, the situation in Somalia was declared a national disaster due to the drought in February 2017 (UNDP, 2018). Poor rains continued into 2017, and impacts included poor harvests, high food prices, food insecurity, livestock losses, and high internal displacement particularly into urban areas (FEWS, 2017b; Malik et al., 2020). Additionally, it was also reported that the drought may have exacerbated conflicts over resources, and a combination of drought and increasing conflict accelerated displacement (UNDP, 2018). Improved disaster risk management and social protection plans in place following the devastating 2011 drought, and the humanitarian response, were able to avert famine (Lwanga-Ntale & Owino, 2020; Malik et al., 2020).

While Strata’s maps for October–December 2016 including all indicators highlight hotspots during this period, users could also select smaller subsets of indicators according to the decisions they are making. For example, if just ‘Drought (agricultural)’ and ‘Exposed population’ are included, much larger areas of the country are shown as hotspots (Fig. 6) as would be expected for this event. While this highlights where people are located relative to drought areas, it does not tell the user anything about who might be more vulnerable or who might be experiencing other stresses at the same time (e.g. conflict events), and therefore the flexibility to select indicators in Strata allows for these

Fig. 4. Hotspot maps for Somalia showing the components of the Strata score (including all indicators listed in Table 1) for the period October to December 2016. As per the calculation described in Fig. 2, maps (a) and (b) have ranges from 0-N where N is the total number of stresses (here 7 Climate and environmental stresses for (a) and 5 Peace and security stresses for (b)), while (c) and (d) have ranges from 0 to 1. Maps from the Strata platform.
more detailed assessments relevant to the given context.

5. Discussion

5.1. Co-designing Strata

A participatory co-design approach can help develop products that are directly informed by the local experts who would use them, and provide the most relevant information for their contexts, so it can be applied to decision making and build capacity for action (Carter et al., 2019; Dilling & Lemos, 2011; Shaw et al., 2009). We have used a co-design approach to develop Strata so that it is informed by user needs and requirements, incorporating local expert knowledge to identify key indicators (Miller et al., 2017). The ability to modify thresholds is also in response to user requests, while all indicators are weighted equally because users were concerned by having different weights as well as not seeing the need to adjust weightings. Users also informed the design of the platform, providing feedback on how they prefer to view data and tested the tool to report on the ease of use. They required transparency in how the data is used and how scores are calculated to enable them to interpret, understand, and use the results. Consequently, Strata provides this detail via information on the platform itself, and in an associated guidebook.\(^\text{16}\) Strata’s co-design process not only ensured the tool was driven by user needs, but it also built the capacity of those who would be using Strata, and the workshops acted as a space for risk science communication. There is evidence that co-design can lead to better uptake of a product (Carter et al., 2019), with capacity building an important element of this. However, we cannot yet demonstrate such effects as we will need to monitor how Strata is used by different stakeholders following its public launch. We will use a combination of approaches including surveys, semi-structured interviews, and usage statistics from the platform to evaluate Strata on its accuracy, uptake, relevance, usability and ethics.

While a co-design process has these key benefits, it is time and resource heavy (e.g. Hirons et al., 2021; Miller et al., 2017; Vogel et al., 2016). There is a need for balance to ensure users can maximise their involvement in the process without requiring too large a time commitment (McBride et al., 2017). We found semi-structured interviews were very informative for gaining detailed insights into particular decision-making contexts, however they can only reach a relatively small audience and do not allow for group discussion and consensus building. We therefore primarily used workshops at key milestones in the design process for users to engage with, allowing users to choose which workshops to attend. For example, there were workshops following literature reviews to develop an initial long-list of indicators, and when a first prototype was available for trial.

Within a large group of users people may think different indicators and thresholds are most relevant, depending on their particular context (Mittal et al., 2021). In Strata we addressed this by allowing users to include or exclude indicators and modify thresholds within the tool. There is also a need to balance user requirements with what is technically and scientifically possible within a tool, and we have not been able to incorporate all user requests within Strata at this point. For example,
not all requested indicators have been included at this stage due to a lack of data availability, such as transhumance migratory patterns. Moreover, some desires could not be implemented in the indicators, primarily in the peace and security basket, due to ethical reasons. For instance, recruitment patterns of armed groups, presence of military factions, and presence of ethnic fractures were ranked high for inclusion during a workshop, but after ethical discussions with users on sensitivities around these themes and potential misuse of this data these variables were rejected. Additionally, some users wanted to be able to view uncertainty information on the platform, however this is not currently implemented and will require further development and discussion with users to determine how best to do this. Effectively communicating uncertainty can be difficult and complex, but is an important demand-driven challenge in risk modelling and assessments (Doyle et al., 2019).

5.2. Interpreting and validating hotspots

The hotspot maps produced by Strata are intended as a first step in a decision-making process, highlighting locations users may want to investigate further. For climate change adaptation or nature conservation practitioners, hotspot maps can help identify where project areas coincide with conflict-affected and fragile regions. They can then work with peace and security experts to ensure that their environmental strategies do not unintentionally exacerbate pre-existing grievances or underlying conflict drivers. Strata can also help evaluate how hotspots vary over the lifecycle of a programme, such as changes in deforestation rates or the locations of populations especially vulnerable to climate impacts. Peace and security practitioners would be able to use Strata to ensure that conflict prevention and peacebuilding initiatives consider where security issues converge with environmental and climate stresses that may disrupt local livelihoods and economies. Other actions users could take based on Strata’s hotspots include identifying where adaptation measures may be required based on where climate stresses and vulnerable populations intersect, or planning interventions following the monitoring of drought and food security conditions.

However, the hotspot maps do not provide all the information required for specific decision contexts. For instance, factors such as climate change adaptation efforts, social networks, and local conflict management institutions, which show considerable variation at local levels and shape resilience to climate stresses and conflict, are not measurable in existing quantitative datasets (Ide, 2017; Ide et al., 2014). Users will bring their own situational understanding to their interpretation of the data, based on expert knowledge, knowledge gathered from local networks, or through complementary research. Strata’s guidebook provides guidance on how to integrate and complement the quantitative data-driven maps with this qualitative in-depth understanding, so that they can nuance and better understand the data in local contexts. For example, users of the tool may have knowledge on location-specific factors with substantial local variation (e.g. where particularly vulnerable households are located within a community, or which communities have adaptive practices they can employ in the case of a hazard), which they can use to identify, within a hotspot region, those particular areas they understand to be more likely to suffer impacts of the stresses occurring. Where this qualitative contextual information is available, it would be useful for tools such as this to look at ways of providing it alongside quantitative maps to deepen situational understanding. In Strata’s case this could include information around adaptation strategies and existing peace negotiation mechanisms.

In particular, quantitative data is not yet able to fully explain the conditions under which climate change might lead to security risks (Ide, 2017). While these pathways have been studied in a range of contexts (e. g. Scheффran et al., 2012; von Uexkull et al., 2016), these cannot be generalized across regions as these links depend on many local factors (the totality of which Strata is unable to map). Therefore, Strata does not highlight potential impact pathways or cascading effects between the stresses. It is up to the user to bring their own expert understanding of pathways and interactions in their specific region in order to interpret the data in this way (Ivits et al., 2019). For example, they may be aware of particular situations in which drought conditions can lead to conflict over the distribution of natural resources, or where there is a higher chance of unrest due to pre-existing intercommunal tensions. Further research is required to investigate how quantitative data tools are used alongside this contextual qualitative understanding in practice.

Validating tools such as Strata can be challenging. Climate vulnerability maps are rarely validated (Preston et al., 2011) due to difficulties measuring vulnerability, with proxy data used for complex socio-ecological processes, a lack of definition of who or what is vulnerable, and the absence of observable data with which to validate future vulnerability (de Sherbinin et al., 2019). However, validation can be achieved using past observed events or expert perceptions of vulnerability (Preston et al., 2009), and stakeholder interviews or literature reviews to evaluate findings in specific locations (Ide et al., 2014). Strata’s aim is to support decision makers by bringing together otherwise disparate data in a clear and transparent way, and so validation should particularly consider what decisions it informs and how it informs them. Involving decision makers in an evaluation process allows for assessment of both the skill of the product and how it has benefited decision making (Hirons et al., 2021). Our validation approach following Strata’s launch will include following practitioners in their use of the tool to see whether the hotspots identify the regions they would expect and how they use the hotspot information. Case studies will also allow us to investigate (1) where hotspots correspond with large impacts on the ground; (2) where different thresholds or indicators could help highlight missing hotspots where impacts occurred; and, (3) where impacts were not seen in regions with mapped hotspots either due to factors not taken into account, such as adaptation strategies, or because interventions were carried out in response to monitoring the area.

5.3. Future developments

Strata will continue to be developed in co-design with users. Future developments will include providing additional indicators in the platform, especially those particularly relevant for other countries and regions. These might include climate and environmental stresses such as tropical cyclones, wild fires and air pollution. Peace and security indicators could be extended to include data relating to resolution efforts, to indicate the various conflict management and peacebuilding efforts that are part of conflict dynamics. Also, conflict datasets other than ACLED, such as the Uppsala Conflict Data Program (UCDP) Georeferenced Event Dataset (GED) data (Sundberg & Melander, 2013), could be added to provide alternative Peace and security indicators. Reporting accuracies vary across datasets and types of events, so it may be useful to include indications of confidence in each of the conflict datasets for comparison.

Additional vulnerability indicators might include access to education or health-related indicators such as disease infection rates. Who or what is exposed to the stresses considered could be extended beyond the total population to include livestock, agricultural areas, the water sector, or specific subgroups of the population such as pastoralist communities, changing which locations are more likely to show up as hotspots. Alternative exposure and vulnerability indicators would be required in these cases. Strata could also be extended to include indicators relevant to applications beyond its initial focus on conflict-sensitive environmental programming and peacebuilding initiatives, such as data provision for monitoring the environmental impacts of companies and assets (Patterson et al., 2022). Furthermore, incorporating the functionality for users to upload their own datasets or draw their own indicator layers for their personal analyses may be possible, but would require consideration around data quality checking and caveats for use of the outputs. To build on Strata’s application as a monitoring tool, an alert system based on user-defined regions of interest and indicators could provide notifications according to the most up-to-date hotspot maps.
Extending hotspot maps beyond the country boundaries may be useful when considering transboundary issues, such as river basin management and water stress. However, it is important to consider where different socioeconomic datasets are available in different countries as these can lead to discontinuities across international borders, which may or may not reflect actual differences (de Sherbinin, 2014). Further work should also consider how to include information related to cascading effects of stresses to impacts on the population within the tool to deepen the information Strata provides to users, if there are specific contexts for which this understanding exists. In particular, this should consider where there may be cascading impacts across geographical areas, such as upstream land management impacting downstream flood risk or agricultural production impacting people in cities, and how this can be highlighted on the hotspot maps.

Currently, Strata focuses on historical and present-day monitoring of stresses, however this will be extended to include future projections. In the workshops users asked for information about where and when risks may increase in the future to inform climate change adaptation planning and building resilience to anticipated disasters. Relevant indicators could include future changes in the likelihood of heatwaves, drought, and floods over coming decades from climate model simulations, or food security projections for the next few months from FEWS NET (FEWS, 2018). A range of plausible future scenarios can represent the uncertainty in future projections, and can be developed to ensure consistency between environmental and socioeconomic changes (e.g. Nicholls et al., 2008). However, climate change vulnerability studies employing future climate projections often show these alongside information about the current status of socioeconomic vulnerability due to data limitations (Preston et al., 2011). In Strata, if users select future projection indicators alongside current status indicators this will need to be clearly highlighted so users can interpret the maps appropriately, as well as identifying if the selected future projections could be inconsistent with each other.

Climate vulnerability assessments and hotspot maps have tended to avoid addressing uncertainty, particularly quantitatively (de Sherbinin et al., 2019; Preston et al., 2011), compensating by describing results tentatively (de Sherbinin, 2014). In future versions, it may be useful for Strata to include an assessment of uncertainty, either quantitatively or qualitatively. Confidence in the datasets could be determined by the source of the data, how frequently the data is updated, or any uncertainty information provided with the dataset itself. Considerations will include how to combine confidence scores for different datasets within the hotspot scores, and how to visualize uncertainty on the hotspot maps.

6. Conclusion

Strata is an online mapping tool, which has been developed in response to user needs for easy access to data and analysis on climate and security risks. Such data often lies in disparate sites, or requires coding skills to access. Strata brings this data together to identify hotspots where climate, environmental and security stresses are co-occurring alongside exposed and vulnerable populations. The hotspots are calculated using thresholds applied to indicators to determine how many are at a level suggesting a stress, with the data layers collated and processed by Earth Blox using Google’s Earth Engine as the back-end. The summed total number of stresses is scaled according to the relative exposure and vulnerability of the population in the location. This approach is customisable by users who can choose which indicators to include in their analysis and adjust thresholds according to their understanding of the local context. Strata has been initially developed for Somalia, and hotspot maps for 2016 demonstrate how the information can be used to draw attention to locations of co-occurring stresses that can alert users to investigate further.

Strata will be extended in the future to include other countries and a larger range of indicators, with development continuing to employ a co-design process with potential users of the tool. Co-designing such a tool can be challenging, as users can have very specific requirements for detailed information, yet it needs to remain simple to use and applicable to a wide range of potential decision-making scenarios. However, through this process we have been able to balance these requirements, developing a hotspot framework relevant to a range of decision-making contexts but with customisable options for users so it can be tailored to specific contexts. While co-design can be time intensive, using a combination of interviews and workshops at different stages of the process allowed us to make the best use of participants’ time and expertise. Working with potential users in this way can ensure actionable data-driven insights within the limits of data availability and understandings of stress-impact pathways.

As a first look tool, users of Strata can rapidly identify locations which may be of concern due to multiple stresses, before investigating these further with both the quantitative data they have available and their expert understandings of how and when impacts on people occur in those locations. There is, however, a need for further research across the broader risk communication sector into how qualitative information can be incorporated with such quantitative approaches, and how quantitative hotspots can be interpreted alongside local contextual knowledge in practice. Nevertheless, Strata is the first tool of its kind for climate security, providing openly-available, easy-to-use, data-driven, customisable data analysis and visualisation. It will ensure that users can make decisions to mitigate the impacts of climate, environmental and security stresses informed by the latest available data, bridging the science-to-policy gap apparent in the field of climate security.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Woodhouse is a co-founder and shareholder of Earth Blox (the trading name for Quosient Ltd).

Acknowledgements

We thank those who participated in the surveys, interviews and workshops for sharing their knowledge and providing feedback to inform the design of Strata. We acknowledge The Group on Earth Observations and Google for access to Earth Engine. This research was funded by the European Union through the EU-UNEP Climate Change and Security Partnership (2017–2022) and by the Government of Norway. Additional funding was provided by the Data-Driven Innovation (DDI) Programme as part of the Scottish Funding Council Beacon Programme at the University of Edinburgh.

Appendices. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.polgeo.2022.102791.

References
