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A Bio+Mine Digital Twin approach to mine closure monitoring

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Abstract

Mine closure demands multidomain, temporally resolved data, yet conventional workflows leave these datasets fragmented and underused when decisions must be made. The Bio+Mine Digital Twin project, based on work carried out at the Sto. Niño legacy mine site in the Philippines, will address this by integrating data from 4 domains into an interrogable data cube from which artificial intelligence (AI) and machine-learning tools can identify cross-domain relationships and model site trajectories through time. A central aim is to establish where cheaper proxies can substitute for intensive sampling. Because the method and learned relationships will be recalibrated to each new site, the outcome will be a modular, transferable workflow template that supports consistent, evidence-based closure practice.

Keywords: *legacy mine, site audit, multidomain datasets, digital twin, machine learning, mine closure monitoring*

1 Introduction

The Sto. Niño mine lies in the Municipality of Tublay, Benguet, Philippines, an area of mountainous terrain that reaches 1,400 m (4,600 ft) above sea level. The region has a temperate highland tropical climate with a dry season between December and May passing to a wet season between June and November. The municipality has a population of around 21,000. The dominant economic sector is agriculture, employing around 29% of the labour force. The mountainous terrain and cool climate is ideal for vegetable farming, with key crops include sayote (chayote) and other highland vegetables. Livestock raising provides additional income for households. Tublay is promoting sustainable practices through organic farming, including coffee cultivation via cooperatives like the Tublay Organic Farming Practitioners Agriculture Cooperative, to enhance economic resilience and help prevent deforestation.

Mining claims in the Tublay area date back to 1907; however, most of the operations responsible for the current legacy site were undertaken between 1972 and 1981. These operations exploited 2 porphyry copper

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deposits: the first an open pit operation in the southwest orebody at Sto. Niño, and the second, an underground block caving operation in the northeast orebody in the Ullman district. Potentially reactive minerals identified in the Sto. Niño orebodies and wastes include azurite/malachite, biotite, bornite, calcite, chalcopyrite, chalcocite, chlorite, epidote, kaolinite, magnetite, molybdenite, muscovite/sericite and pyrite (Herrington et al. 2023).

Two types of mining operations were undertaken on site from 1972 to 1981: open pit in the southwest orebody and underground block caving in the Ullmann orebody. Tailings was pumped underground from surface thickeners at the mine site to a tailings storage facility (TSF) in the Fortuna Creek, a tributary of the Amburayan River in an adjacent valley to the north.

The entire mine site and TSF were subsequently left unrehabilitated after closure in 1982 (Figure 1), but since that time, local people have moved back and are both living on and actively farming on the old mine site and waste facilities (Alonzo et al. 2023). Underground, small-scale mining for gold and base metals is reportedly being carried out in the Ullman region, above the former underground block caving operation but is informal and visibly has a negligible additional impact on the site.

Figure 1 Abandoned 200 ft-diameter tailings thickener left at the mine site

1.1 Bio+Mine project overview

The Biodiversity Positive Mining for the Net Zero Challenge (Bio+Mine) project (https://bioplusmine.earth), funded by the UK's Department of Environment, Food and Rural Affairs (DEFRA) under the Global Centre on Biodiversity for Climate program (https://www.gcbc.org.uk/), focused on the Sto. Niño legacy mine site and undertook work focused on 2 aims: to understand what happens to geological, environmental and socio-economic factors when such sites are left abandoned and investigate appropriate remediation and intervention options that could deliver the most positive impact, while working closely with the local community supported by the biodiversity of the local environment.

Phase 1 from August 2022 to March 2023, began with an intensive program of engagement with the local communities, politicians and other stakeholders prior to factually assessing the legacy issues on the ground. The methodologies and results from this engagement program have been documented in Alonzo et al. (2024, 2025). Following agreements resulting from extensive consultation with local stakeholders at all levels of administration, an onsite surveying and sampling program was developed. A suite of measurements was made with the goal of providing an up-to-date audit of the site. The data were used to prioritise, inform and design interventions to improve site conditions. These interventions became the core of objectives in Phase 2 that commenced in April 2023.

Phase 2 interventions included direct water remediation strategies (Pocaan et al. 2025). Another key aim was to upcycle the agricultural expertise of the local population in the development of biodiversity-positive approaches to agri-ecosystems, particularly systems that could immobilise, neutralise or recover problematic mobile components like metals at the site. The ongoing interventions include ways to encourage natural carbon sequestration and biodiversity gains that could also be incorporated into a full-scale system of intervention for future years. Site-specific strategies are thereby underpinned by the knowledge, skills and practices of the local communities.

Phase 2 results indicated that a further Phase 3 was needed to investigate the sustainability of the implemented Phase 2 and furthermore develop an effective evaluation tool to monitor future performance of the site. Funding was secured from the Claude and Sofia Marion Foundation in 2025 for Phase 3 starting with Bio+Mine Grow, a project that works with the local stakeholders to develop a sustainable community-driven program for the Sto. Niño site beyond the end of the program, leading into the Bio+Mine Digital Twin project in 2027 which seeks to develop a transferable data cube–driven approach to mine closure monitoring, based on the Sto. Niño Bio+Mine experience, that can be tested using artificial intelligence (AI) tools as a novel way to monitor the socio-environmental performance of any mining project right from inception through operation and into mine closure.

2 Bio+Mine outputs

From project inception, the team recognised the need to collect data from the 4 different data domains of social study, geosciences, hydrology and biosciences. More traditional techniques were augmented using remote sensing embracing both satellite and newly collected drone data from the site. The 2-year data collection program yielded extensive geospatially referenced datasets from the 4 domains that have since been used for a range of purposes (Table 1). Much of the site-specific technical data have been compiled into a geographic information system (GIS) platform linked to a digital database of the range of results. The social data is held in a separate database for GDPR and operational reasons, while much of the genomic data are held in a separate database due to considerations of size. From the work to date, it is recognised that a much more sophisticated data cube is needed to hold the complex datasets from which a true digital twin can be created and thus greater value can be derived using more advanced interrogation of interrelated datasets, including AI tools.

Table 1 Summary table of datasets collected at Sto. Niño between 2022 and 2026

Data domain	Data type	Variables	Number of samples	Spatial resolution	Temporal coverage	Storage format
Geoscience	Rock sample	Mineralogy; geochemistry	161	Ad hoc: safety and access considerations	November 22; November 23	XLS, TXT, JPEG
Geoscience	Tailings sample	Mineralogy; geochemistry; environmental DNA	20	Two cored drillholes	November 23	XLS, TXT, JPEG, FASTQ
Geoscience	Soil elemental composition by XRF	Major and trace elements and oxides; pollution/contamination indices	15 soil samples (5 site classes × 3 quadrats)	Quadrat-level at control site	November 22	XLS
Geoscience	Soil multi-element chemistry by ICP-MS	Multi-element concentrations in ppm and %; priority metals/metalloids including Ni, Zn, Mn, Cu, Pb and As; pH; derived pollution indices	15 soil samples (5 site classes × 3 quadrats)	Quadrat-level at control site, TSF, waste dumps A and B and Bugtong Farm	November 22	XLS
Bioscience	Freshwater environmental DNA	Bacteria, archaea, eukaryotes richness and composition	50	All river and spring sources	Annual 6 monthly November 22 to November 23	FASTQ, XLS
Bioscience	Soil environmental DNA	Bacteria, archaea, eukaryotes richness and composition	300	Site-wide distribution	November 22	FASTQ, XLS
Bioscience	Plant rhizosphere environmental DNA	Bacteria, archaea, eukaryotes richness and composition	25	Site-wide distribution	November 22	FASTQ, XLS
Bioscience	Plant identifications	Species, locations	250	Site-wide distribution	November 22	JPEG, CSV, XLS
Bioscience	Plant and rhizosphere elemental composition and	Element concentrations in shoots, roots, whole-plant samples, and rhizosphere soil; fresh/dry mass and water content;	45 fraction-level XRF measurements across 15 types	Plant- and fraction-level within quadrats at control site, TSF, waste dumps A and B, Bugtong Farm	November 22	CSV, XLS

Data domain	Data type	Variables	Number of samples	Spatial resolution	Temporal coverage	Storage format
	metal-uptake indices	bioconcentration factor, translocation factor				
Hydrology	Water quality parameters	Metal concentrations, anion concentrations, in situ parameters	98	River, small streams, spring sources/rock aquifers	Quarterly to monthly, from November 22 to May 26	CSV, XLS
Social	Social data/resident interviews	Socio-economic data (land use, agricultural needs and behaviour), water and waste water usage	120	Distributed across the study area	November 22 and June 26 and various ad hoc	TXT, MP4, JPEG
Geo/Bio/Hydro/Social	Lidar	X, Y, Z coordinates – intensity, return number, number of returns, GPS time, scan angle, classification	2 km^2 coverage in detail, further ad hoc coverage	3 cm/pixel	November 22 and March 23, various ad hoc to April 26	LAZ, LAS, GeoTIFF
Geo/Bio/Hydro/Social	Multispectral	Reflectance spectral bands	2 km^2 coverage in detail, further ad hoc coverage	3 cm/pixel	November 22 and March 23, various ad hoc to April 26	Spectral binary file, JPEG 2000

XRF = X-ray fluorescence; ICP-MS = inductively coupled plasma mass spectroscopy

2.1 Data disciplines and data types

2.1.1 Social

To support the development of a site-specific system that was firstly well grounded in local knowledge and practices, a social–ecological–technological systems (SETS) framework was adopted for the project. This framework was appropriate as it positions ecosystem services within local contexts (Frantzeskaki et al. 2019) and as products of interactions among socio-economic-demographic, ecological and technological subsystems (Pickett et al. 2001). Its application ensured that the system was informed by diverse data, with emphasis on social data, and required stakeholders (communities) to co-design the rehabilitation project while assessing social drivers and community and environmental benefits. The SETS framework also guided a developmental engagement approach: In Phase 1, the focus was informing, consulting and engaging the community. Phase 2 involved developing appropriate partnerships to achieve shared goals and Phase 3 of the project is aimed at empowering communities to implement intervention programs and ensure that the intervention program is sustainable. A comprehensive description of the Bio+Mine project and methodologies is provided in Alonzo et al. (2023), Armstrong et al. (2023) and Herrington et al. (2023).

A household enumeration survey was conducted, covering all households in Sto. Niño, Tublay, Philippines. Data were gathered through a structured social mapping questionnaire administered to household heads or their adult representatives. All households participated in the survey. The questionnaire collected information on household demographics, geographic location, socio-economic conditions, residency, health status, community participation and livelihood characteristics. In addition, respondents provided spatially relevant information that supported the identification of critical facilities, lifeline utilities, and locally perceived hazard-prone areas. The resulting data were encoded, validated and analysed using descriptive statistics and community-based spatial profiling to generate a comprehensive social and spatial characterisation of the site.

To illustrate the analytical process with our social data, interview data describing negative perceptions of external researchers in legacy mine rehabilitation will be analysed using grounded theory. Statements such as ‘external researchers do not understand our local context’ and ‘we rarely see the outcomes of the research’ will be coded as a lack of trust and poor knowledge exchange, which will be grouped into the category stakeholder trust and engagement through constant comparison. Situational analysis will then map this category in relation to stakeholders, rehabilitation processes and contextual factors, with the resulting relationships informing the data cube as an analytical dimension linked to stakeholder group, rehabilitation phase and evidence source.

2.1.2 Geoscience: rock and waste materials

Aside from climate, geology is the fundamental control to the nature of the site. A range of rock and waste samples were therefore collected at Sto. Niño that would permit the characterisation of the bedrock geology and the various mining wastes. This work is discussed in more detail in Herrington et al. (2023). The rock and waste samples were collected using standard sampling methodology and protocols from different parts of the site representing unmineralised bedrock (control), mineralised bedrock (artisanal mining site, Ullman adit), TSF, waste dumps and from a rehabilitated farmed field.

Rock samples, waste materials and selected soils were selected for more detailed chemical and mineralogical characterisation to investigate which elements are highly elevated and the mineral phases in which these are deported. The samples were analysed using a combination of techniques that included bulk whole-rock chemistry using inductively coupled plasma atomic emission spectroscopy (ICP-AES) and inductively coupled plasma mass spectrometry (ICP-MS). Mineralogy was determined using X-ray diffraction (XRD), coupled with spatially resolved mineralogy and mineral chemistry analysis using scanning electron microscopy (SEM) augmented by energy dispersive X-ray spectroscopy (EDX) where appropriate. Spatially resolved mineralogy and mineral chemistry was achieved on rock samples using electron microprobe (EPMA) and the modal mineralogy was evaluated using a combination of automated SEM mineral analyser and XRD analysis. The data were compiled into a GIS database. An example of derived information is shown in Table 2.

Table 2 Summary table of results summary from analysis of mine tailings

Minerals from tailings		Chemistry of tailings		Chemistry	
Rock forming minerals	**Trace minerals**	**Rock forming elements**	**Trace elements**	**Concentration ranges**	
Quartz	Chalcopyrite	Silicon	Copper	Copper	0.014–0.11%
Plagioclase	Pyrite	Aluminium	Manganese	Manganese	0.043–0.26%
Potassium feldspar	Goethite	Calcium	Phosphorus	Zinc	0.005–0.079%
Hornblende	Hematite	Magnesium	Zinc	Sulphur	0.1–0.14%
Chlorite	–	Potassium	Lead	Lead	0.004–0.014%
Clay	–	Sodium	Sulphur	–	–

2.1.3 Bioscience: plants and soils

Soil and plant samples were collected at the same time from the site during the wet season to optimise plant identification across 4 focus areas: a control site, waste dump A, waste dump B and the TSF. Soil samples were analysed for major elements and thus became part of the geoscience dataset. Three representative sampling quadrats, each 100 m^2 in area and 10 m apart, were established at each key area. Soil samples were collected in 5 locations within the quadrat (corners and centre), and each representative sample was a composite of the 5 sites.

Bulk soil samples from the site were air-dried, sieved and weighed. Soil pH was measured and particle size analysis was carried out on the <75 µm fraction. Part of the <75 µm fraction was used for the clay separation analysis using XRD on smear mounts. The soil samples were analysed using XRF for their major chemical compositions combined with XRD to determine mineral components. Digests of samples were then analysed using ICP-AES and ICP-MS on both aqua regia and lithium metaborate digests to determine major and trace element contents. Selected samples were analysed using the automated SEM and EPMA to determine modal mineralogy and deportation of trace elements (see reported in the geoscience). Total carbon and sulphur were measured, and organic carbon was calculated separately from non-carbonate carbon.

Plant data were developed from random sampling within sample quadrats, mindful of abundant species at the site. Plants included wild species across the site, as well as a range of cultivated crop plants (Figure 2) that were being used at the site.

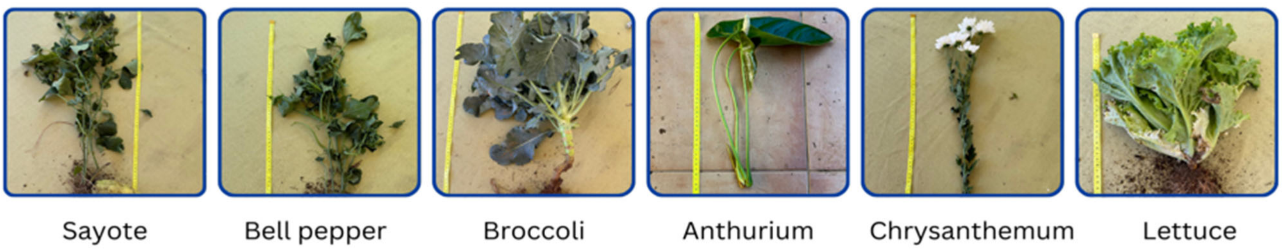

Figure 2 Photographs of collected plants used by the local community as crop plants

Plants were identified morphologically and for validation, plants were photographed and voucher specimens of uncommon plants, including specifically hyperaccumulator species (Figure 3), were recorded. The study incorporated indigenous knowledge about mine site plants (Andalan et al. 2024).

Whole-plant samples were pressed for morphological identification, and leaf parts were placed in a collection bag for molecular identification. The rhizosphere soil was also collected and then air-dried and submitted for chemical analysis. Shoot and root parts were thoroughly washed with tap and distilled water and then freeze-dried.

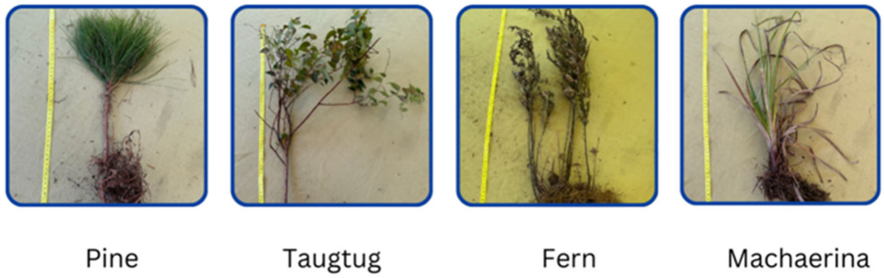

Figure 3 Photographs of plants identified on waste dump B that are shown to be copper hyperaccumulators

2.1.4 Metagenomic (eDNA) samples from soils and water

The project also yielded a range of environmental DNA (eDNA) data from material collected from soils, water and the rhizosphere. Soil microbiota is an important bio-resource for sustainable agriculture since beneficial microorganisms augment plant growth, and in addition specific microbiota can be implicated in mineralogical reactions occurring at rock, soil and water interfaces. A series of 16SrDNA gene data were collected from bacteria and archaea (16S rRNA sequencing is a molecular technique used to identify and classify bacteria and archaea by analysing the highly conserved 16S ribosomal RNA gene), fungal internal transcribed spacer (ITS) has been isolated (fungal ITS sequencing is a high-resolution method for identifying fungal species and analysing fungal community composition using the internal transcribed spacer regions of rRNA genes) and eukaryote 18S ribosomal RNA has been identified (abbreviated 18S rRNA it is a part of the ribosomal RNA found in eukaryotes. Similar to the prokaryotic 16S rRNA, the genes of the 18S ribosomal RNA have been widely used for phylogenetic studies and biodiversity screening of eukaryotes. Distinct differences in bacterial populations have already been noted in waters collected from mineralogically impacted waters and similar patterns regarding contaminated soils are likely (Figure 4).

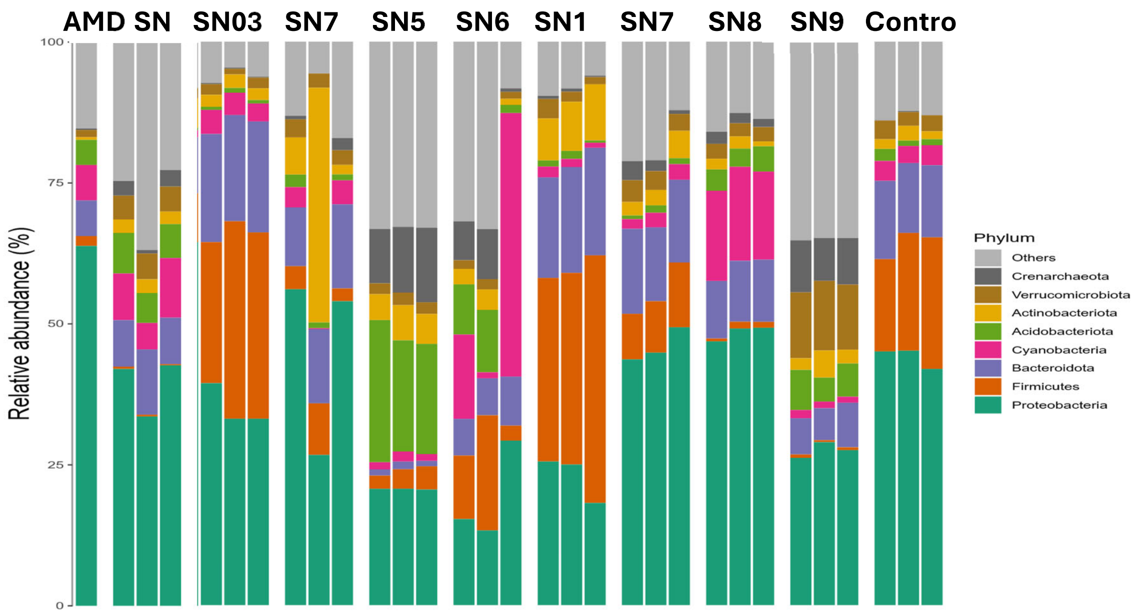

Figure 4 Diversity in bacterial populations found in eDNA sampling across water courses covering the mine site

2.1.5 Hydrology sampling

Water is the most important resource for the local community who rely on this for agricultural and domestic purposes. Water sampling has been conducted numerous times since 2022 across the Sto. Niño site during both wet (November) and dry (April) seasons. Collected samples were filtered to recover undissolved solids in addition to being analysed for dissolved components. In addition, at many of the sites, extracts for eDNA were prepared (see section above). Physicochemical and geochemical properties were determined directly from the water samples and samples were then acidified and stabilised in the field prior to dispatch for follow-on analysis.

In situ data include pH and oxidation-reduction potential, electrical conductivity and temperature. Filtered solids were recovered and dried to determine total suspended solids. Other physical analysis included total hardness and alkalinity. Dispatched samples were then analysed for dissolved metals: Al, Sb, As, B, Cd, Ca, Cr, Cl, Cu, Fe, Pb, Mg, Mn, Hg, Ni, K, Se, Na and Zn. In addition, cations and anions analysed include nitrate, nitrite, phosphate, sulphate and silica. These results have informed the development of local plan for water resource utilisation as well as helping to develop a novel water pollution index in mining-impacted environments (Balboa et al. 2025). This index has been used to facilitate identification of sites targeted for intervention at the site (Pocaan et al. 2025).

2.1.6 Remote sensing

During the first 2 phases of the project, public domain satellite imagery and limited InSAR data were acquired, along with multimodal drone imagery surveys from the site that yielded datasets including digital elevation model, lidar and multispectral information at a variety of resolutions. A detailed area of around 2 km^2 was focused on for the drone surveys in different levels of detail in 2 programs – during the dry and rainy seasons, respectively. Visible, multispectral and lidar images were collected using both a DJI Phantom 4 and a DJI Mavic 3 drone with various sensor loads. The remote sensing data offer a new tool to augment the use of ground-based traditional techniques of sampling the geology, hydrology and biospheres. The lead team from Imperial College has been developing several geospatial AI solutions to analyse and interpret these data. One useful output from this work is multispectral maps that can be interpreted in terms of crop health. Outputs from these solutions would be incorporated into data layers that would contribute to the data cube. A figure derived from these datasets is shown in Figure 5.

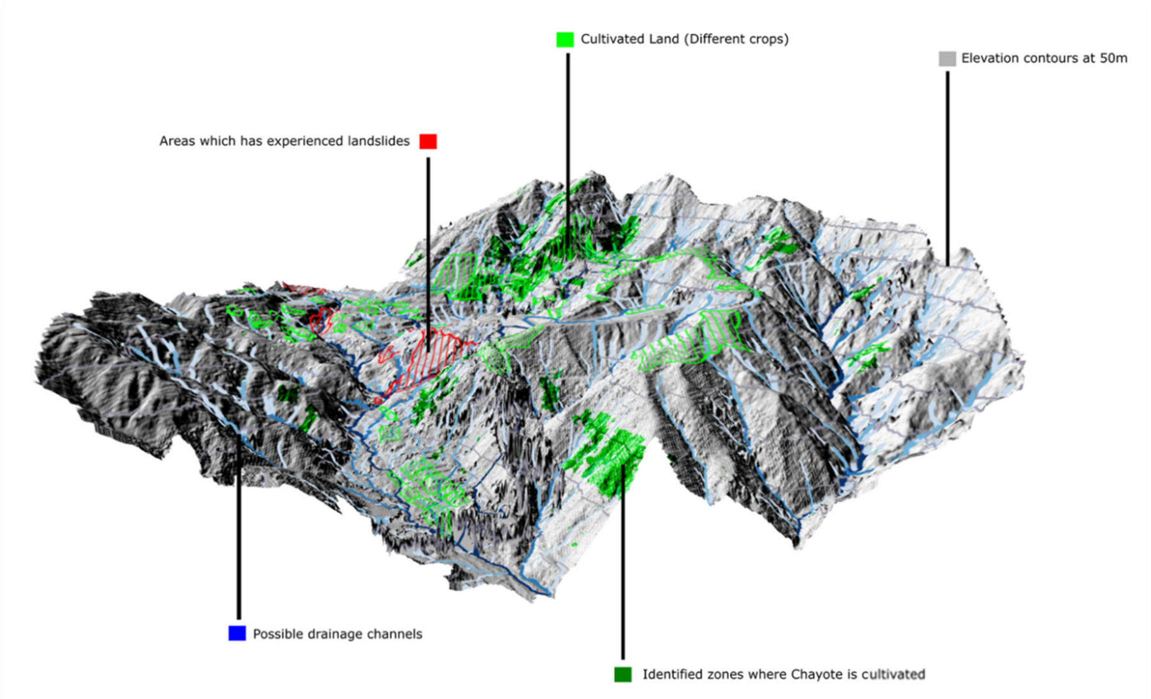

Figure 5 Annotated 3D view of the digital elevation model of the study site generated from lidar data

3 Developing a data cube

To progress our project towards the development of more useful monitoring and planning tools, particularly integrated AI tools that might be used to monitor site performance, we are working on the development of a sophisticated data cube (Figure 6) from the extensive multidisciplinary datasets discussed above that will be able to manage the multidimensional datasets that we have created. From this, we will create an effective digital twin of the mine site. The current flat data structures that hold our data include spreadsheets and relational databases and are limited in their functionalities. The quantitative data we have includes both point and continuous data, both structured and unstructured datasets, and make the data more useful, we need to map them across layers to examine spatial correlations. Data cubes enable a more efficient exploration of complex datasets in 3 or more dimensions. From this we aim to map more specific geology–biology–hydrology interactions. By integrating SETS, our methodologies will allow us to follow a systematic approach to obtain more qualitative data. Grounded theory methodology enables insights to emerge from the data, which we recognise needs contextualising. Situational analysis can then be applied to 'map' experience to the wider context and will link back to the data cube.

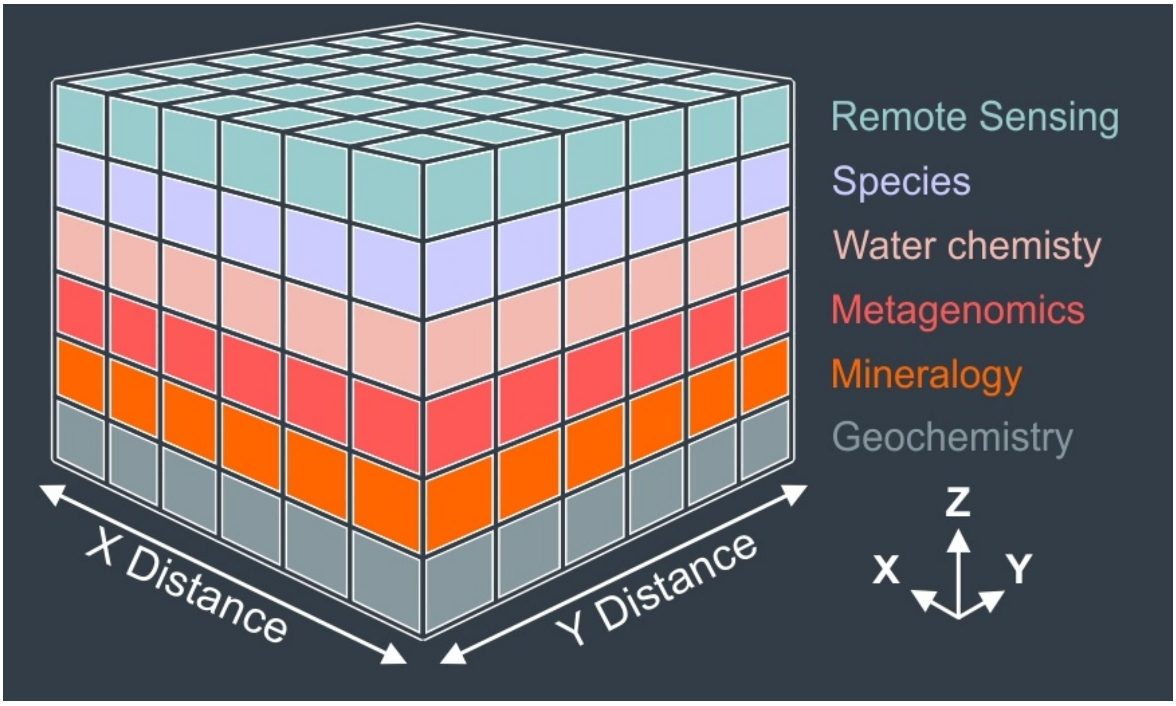

Figure 6 Simplified schematic diagram of the scope of the Sto. Niño data cube

4 Developing artificial intelligence tools

The multidimensional data cube provides the structured foundation from which AI and machine-learning tools can be developed to monitor site performance and support closure planning (Figure 7). Enabling spatial and cross-domain correlations to be mapped simultaneously opens analytical possibilities that conventional flat data structures and single-domain workflows are simply not designed to deliver. Within this architecture, supervised classification and unsupervised clustering can be applied across the combined geochemical, remote sensing, metagenomic, physical and social datasets collected at Sto. Niño. As a worked example, clustering of the 16S rRNA eDNA and water chemistry data has already separated sites impacted by acid mine drainage (such as SN5) from cleaner waters across the site, a signal that directly informed where a regenerative water quality intervention was prioritised (Balboa et al. 2025; Pocaan et al. 2025). A key objective is to test whether cheaper, more easily collected variables, such as multispectral reflectance or in situ pH and electrical conductivity, can reliably predict the more expensive laboratory and sequencing results. Where such relationships hold, routine monitoring could lean on the low-cost proxies while reserving intensive sampling for locations where the model is least certain.

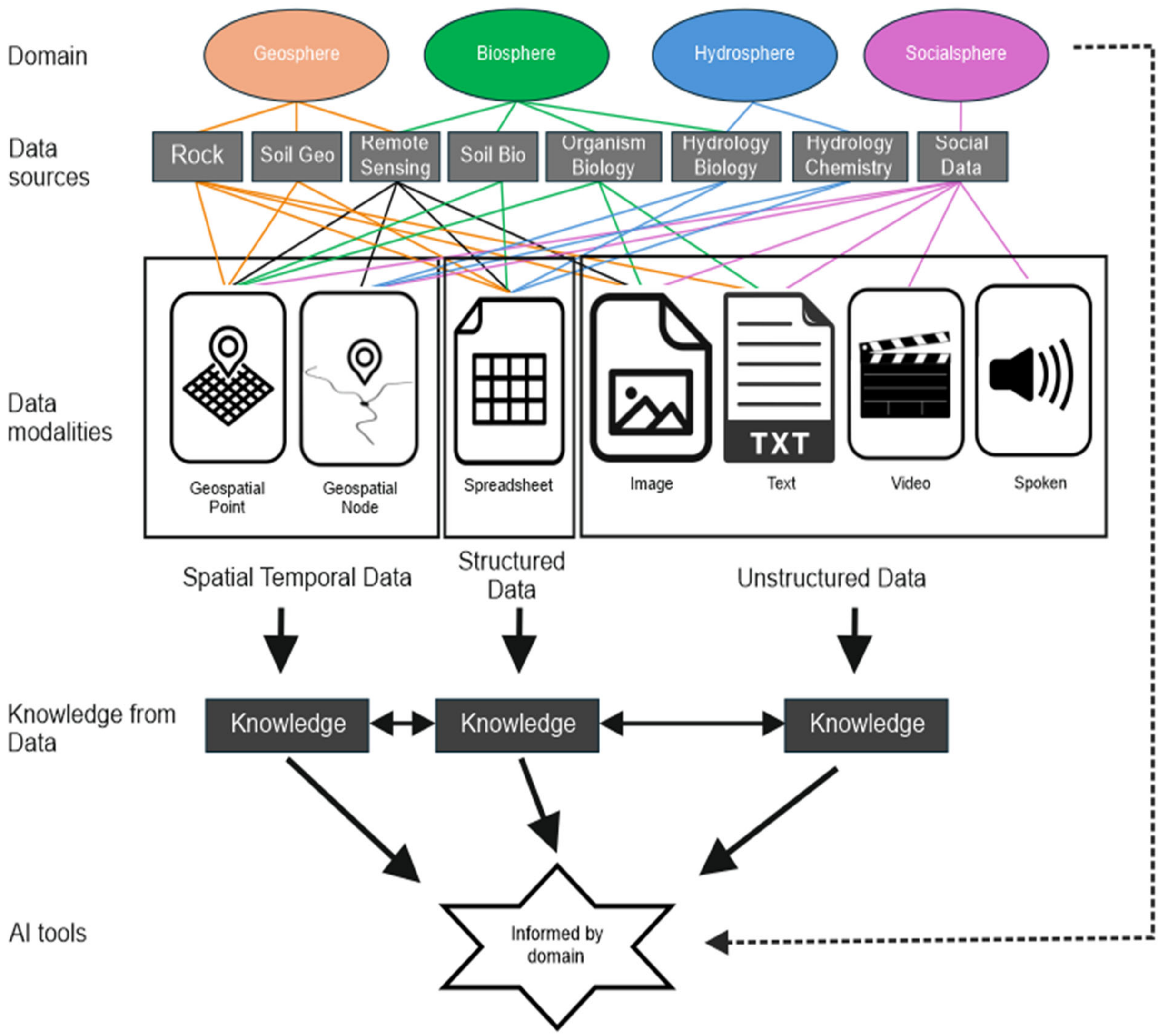

Figure 7 Key components in the development of cross-domain multimode data fusion platform for the project

For the mining industry, this points toward a more strategic, evidence-based approach to closure performance. Rather than the analytical results transferring directly, it is the workflow and the modelling approach developed at Sto. Niño that are portable, recalibrated to the geology, hydrology and social context of each new site. This has the potential to reduce the time and resource burden of closure monitoring while improving consistency. It also enables operators to monitor site recovery proactively, refine interventions in near real time, and maintain a clear, defensible record of performance.

A deliberate design principle is transferability. Because Sto. Niño has been characterised across all 4 domains at high data density, the relationships learned there can serve as a pre-trained foundation rather than a single-site result. Applying them at a new mine with different geology and hydrology requires only a limited, targeted dataset to recalibrate the models to local conditions, an approach analogous to transfer learning in which a model trained on a data-rich case is fine-tuned to a related setting with far fewer new data. The Sto. Niño models supply the structure of the relationships, and the new site supplies only enough data to adjust them. In this way the Bio+Mine data cube becomes a transferable closure engine rather than a static record, improving as each additional site is added and supporting the transition towards more sustainable cradle-to-cradle mining (Herrington & Tibbett 2022).

5 Conclusions

Since inception, the Bio+Mine project has successfully achieved the following initial goals:

- It has working positively with an impacted, largely indigenous, community to set up a rehabilitation program at an abandoned problematic mine site.
- An extensive audit of the site from a geoscience and ecosystem point of view was undertaken, using novel tools such as eDNA and remote sensing as well as more traditional geoscience, hydrology and biological tools that have yielded a series of geospatially anchored, time-stamped datasets that characterise the site.
- It has led to a series of realistic interventions that will lead to a more sustainable future for the site and its population.

This work clearly demonstrated that conventional workflows can leave these datasets fragmented and underused when decisions for the site must be made.

Our new proposed Bio+Mine Digital Twin project is looking to use the case study of the Sto. Niño site to develop a more generic and transferable data model that – together with a set of tools that include innovative AI machine-learning tools – can be used to better monitor and manage the performance of mine sites from the start through to mine closure.

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