Mine Closure 2021 – AB Fourie, M Tibbett & A Sharkuu (eds)
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https://papers.acg.uwa.edu.au/p/2152_46_Ashby/

Exploring abandoned mines through a public lens

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Abstract

Research suggests that there are potentially millions of abandoned mines around the globe. As such, it is highly probable that these operations have the potential of resulting in a magnitude of social and environmental issues. However, there is limited literature on their social impacts specifically to a local community. To explore this issue, we investigated four case studies through a literature review using a wide range of white, grey and peer-reviewed literature. We examined case studies in Australia, China, Europe, and the USA. From this preliminary review, we determined that all have a significant number of abandoned mines. We examined these Case Studies as their respective economies rely heavily on the mining industry. The terminology ''abandoned mines'' is often ambiguous and potentially not well understood. Our research shines the spotlight on the problem and examines novel solutions to manage issues associated with abandoned mines. We also examine the closure requirements for abandoned mines in a broad setting, and how these operations can be successfully monitored using Unmanned Aerial Vehicles (UAVs). Accordingly, our aim was to explore a wide range of jurisdictions and determine how local communities are affected by abandoned mine, and where UAVs technologies are commonly utilised

Keywords*: abandoned mine; environmental legacy; social impact; environmental impact; unmanned aerial vehicle*

1 Introduction

The number of abandoned mines across the globe is likely to be in the millions. These abandoned sites vary from small shafts and surficial workings which may present minor or only nuisance residual impacts to vast mine voids or pits over many square kilometres with serious environmental legacies. However even small-scale mining can lead to acute and ongoing environmental impacts if it has been intensive or unregulated. It is unlikely the true number of abandoned mines will ever be known, primarily because of the difficulty in accounting for them, their dynamic nature (mines are closing all the time, of which some may be reopened at a later stage) and because they are defined inconsistently by different jurisdictions. In, Australia for instance, a legacy or abandoned mines are broadly defined as: 'mines where mining leases or titles no longer exist, and responsibility for rehabilitation cannot be allocated to any individual, company or organisation responsible for the original mining activities' (Department of Industry, Innovation and Science, 2019). Whereas in Canada, the term abandoned mines is defined as abandoned mine" describes sites where advanced exploration, mining or mine production has ceased without rehabilitation having been completed (Mackey 2000). And in the, for instance, the USA defines such lands as "Those lands, waters, and surrounding watersheds contaminated or scarred by extraction, beneficiation or processing of ores and minerals…" (EPA 2018). This happens when owners are insolvent, there has been a significant change in ownership or simply because the passage of time makes links to previous owners unclear or not legally binding. In other countries, regulations requiring companies to clean-up the mine site following cessation of mining lack power or are non-existing. In most cases it is left to government to fix the problems, rehabilitate the land and attend to any safety or environmental legacies. Although the residual environmental impacts of abandoned mines (and their mitigation and management) have received much research attention, less effort has been directed to social and economic challenges following mine abandonment (Bennett 2016). It is also probable that in some circumstances abandoned mines become legacy sites over time, which means it may be too late to find a party who can be held responsible for site rehabilitation, for which the state and public will need to carry the can (Ashby et al. 2016).

To further explore these issues, we investigated four regions and present case studies from each of these areas which demonstrate the local circumstances and regional differences around how abandoned mines are created and managed. Accordingly, our aim was to explore a wide range of jurisdictions and determine how local communities are affected by abandoned mines. This was done via a literature review using of a wide range of white and grey literature and peer-reviewed scientific journals. Our work particularly focussed on the socio-economic impacts following abandonment and how they may be mitigated or managed, but also briefly examines how Unnamed Aerial Vehicle (UAVs) are used to monitor such operations and examines a wide range of other contexts and applications.

Our research, whilst preliminary shows that there has been significant uptake in the use of UAV technology in mining applications (Mekert & Bushell 2020). This increase is reported to be due to availability of multispectral, hyper spectral, thermal, light and LiDAR and radar technologies (Raval 2018). In this context, such technologies were utilised to examine legacy mining operations in New South Wales, Australia, focusing on the environmental impacts associated with heavy metals to the Great Blue Mountains World Heritage Areas. This study highlighted the need further develop, refine and enhance UAV technologies, when monitoring ecological changes in highly sensitive environments on post mining landscapes. Research in China and Europe has also identified significant gaps in relation conventional surveying and mapping technologies, noting that these systems capture safety and ecological matters in two-dimensions, this of concern as the number of abandoned mining operations continues to rise. Thus, the introduction of 3-dimensional UAV technology (models) is showing positive results due higher accuracies and the implementation of powerful statistical ecological monitoring tools to capture ecological issues associated with abandoned mining operations (Deng 2021). Our focus was to demonstrate that UAV have a huge potential of being utilised to monitor abandoned mines in varying environments and or settings. UVA provide a safer platform as they are to be deployed in areas of extreme danger, such as areas prone to subsidence, unsafe landforms and areas of acid mine drainage and or gaseous and toxic environments, for instance underground operations and high-risk tailings dams or former processing plant locations. Remote sensing (UAV) technologies have also shown positive results in relation to capturing environmental issues around post closure, specifically data gaps in relation to restoration, rehabilitation and ecological monitoring (McKenna et al 2020). Additionally, when reliable data in relation to abandoned mines is often scarce and problematic to source in many instances (Park et al 2020).

2 Regional case studies

2.1 Australia

It is estimated that there is greater than 50,000 abandoned mines across Australia (Parbhakar-Fox 2014), however the actual number is difficult to precisely quantify. This is because the methods used to capture and record this this type of information varies within each Australian jurisdiction (Pepper et al. 2014). To further compound this issue the terminology around “abandoned mines” and “legacy” also varies both spatially and temporally (Unger 2013). Figure 1 shows the spatial location of abandoned mines in each Australian jurisdiction where data is available.

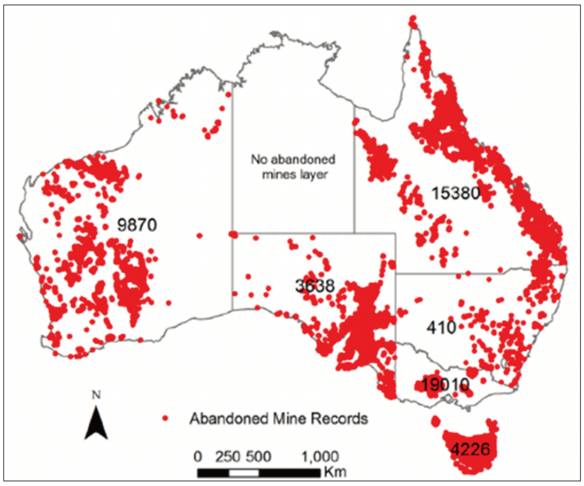

Figure 1 Spatial location of abandoned mines in each Australian jurisdiction adapted from (Unger et al. 2012)

The environmental issues associated with abandoned mines vary from loss of biodiversity, acid mine drainage (AMD), water quality and poor or incomplete rehabilitation (Pepper et al. 2014; Unger, 2013). Abandoned mines in Australia are generally a result of a long history of 'boom and bust' times akin to gold rushes in the late 1890s to modern day iron bonanzas (Mudd 2013).

Such riches have indeed resulted in massive injections to the Australian economy. However, paradoxically large areas in Queensland, Northern Territory, Western Australia and Tasmania already show evidence of AMD, water quality issues and poor rehabilitation practices as a result of abandoned mines. The cost to rehabilitate and remediate such mines is expected to be in the billions (Mudd 2013; Figure 2).

Figure 2 Example of acid mine drainage at Redbank Mine, Northern Territory currently in care and maintenance (Mineral Policy Institute 2019)

From a social context, abandoned mines where pit lakes have established, pose significant issues to humans and wildlife. For instance, wildlife that use pit lakes as a water source may ingest water that is contaminated by heavy metals which in some circumstances can results in bioaccumulation issues. Stock may also fall due to steep side walls. Humans are also at risk of falls and contracting Ross River fever and encephalitis from the contaminated water if ingested (McCullough & Lund 2006; Figure 3).

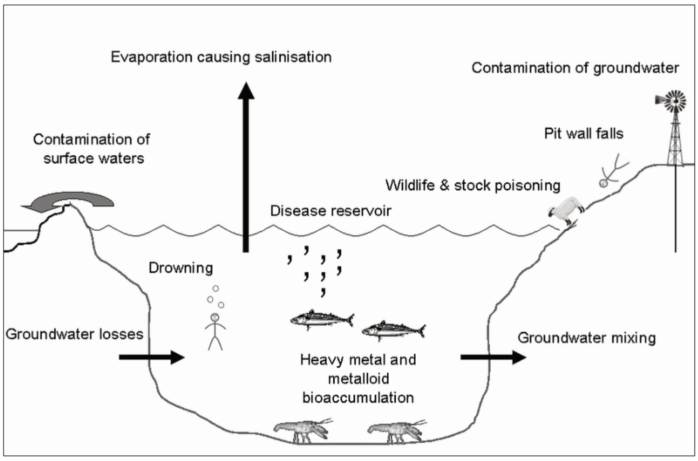

Figure 3 Social and environmental issues associated with abandoned pit lakes (adapted from McCullough & Lund 2006)

2.2 European Union

The number of abandoned mines across Europe is likely to be over 100,000. The number of abandoned mines in the UK alone is in the thousands, with an estimated 10,000 in Sweden and 4000–6000 across France (Mayes et al. 2009; Venkateswarluet al. 2016). Although the number of active mines across Europe is small compared to Australia, Africa and North America, the long history of mining across this region, some of which dates to Roman and even earlier periods, means the effects of mining can still be seen across the landscape in many areas, especially where mining was highly concentrated. However, given the time periods involved many old mine pits have been purposely and successfully converted to other land uses. Some well-known examples include old quarries now used as major wetland conservation areas across the UK and the conversion of derelict coal mine voids into major recreational lakes in eastern Germany. The opportunities created for socio-economic development post mining are realised much more in Western Europe compared to other regions.

The Cartagena–La Unión Mining District located in the Murcia Region of south-east Spain covers an area of 50 km2 and is a good example of a European mining district undergoing a recent socio-economic transformation. This semi-arid area of Spain has experienced a long and complex history of mining, mineral processing and smelting going back over 2000 years, starting in the Iberian period, being particularly intensive during the Roman Empire, and then rising and falling until ceasing in the early 1990s. The main mined ore deposits have been iron, lead and zinc (Oen et al. 1975). The area has had several major mining booms in modern times. Major advances in metallurgy and new ore discoveries in the mid to late 19th century encouraged extensive underground mining (via shafts, tunnels and galleries) which attracted thousands of people to the area; much of this mining was uncontrolled and opportunistic with little regard for the environment or human welfare (Egea-Bruno 2003). Near-surface high-grade ore was effectively mined out by early 20th century which prompted multinationals to gradually take over and they combined large open pit (cast) mines with new extraction techniques to more efficiently mine the remaining low-grade metal ores. Huge amounts of ore were extracted in this fashion, with the amount mined from 1940–1990 being about the same as had been removed in the previous 2000 years (Conesa et al. 2008). However, by the late 1980s ore reserves were dwindling, combined with low global metal prices and increasing concern over environmental impacts emanating from the mining, the mines were forced to close in 1991 (Egea-Bruno 2003).

The socio-economic impacts of mine closure in the area have been profound due to the economic dependence on mining for many decades. The residential population of the local government area declined from approximately 30,000 in 1990 to 13,900 in 1991, and unemployment rates rose to more than 20% (Conesa et al. 2008). In addition, there were many ongoing environmental legacies after mine closure (Table 1). The major ones stemmed from the large amounts of tailings deposited in the landscape, from unconsolidated tailings of the old underground mines to large tailings dams (amounting to some 160 ha; Martínez-Orozco et al. 1993). These tailings have spread via soil erosion (both wind and water) and pollutants have been transported by water runoff and deep infiltration to contaminate agricultural land, waterways, aquifers and urban areas, causing ongoing health and toxicity problems to humans, crops and aquatic life (Conesa et al. 2006; Conesa & Schulin 2010; Robles-Arenas et al. 2006). Furthermore, tailings were routinely dumped in rivers, wetlands, estuaries and nearby marine environment which has resulted in severe heavy metal pollution and acidification of these ecosystems (Martinez-Frias 1997; Marín-Guirao et al. 2005). Many years later these pollutants persist in sediments, surface soils, groundwater and the wider food chain (Conesa & Schulin 2010; Khademi et al. 2018). Other impacts since closure have included human accidents, landslides and soil subsidence (Conesa & Schulin 2010).

Despite these serious socio-economic and environmental legacies, new industries and economic opportunities have emerged in recent years around mining heritage tourism, which increasingly attracts local and international visitors interested in the long history of mining in the region (Conesa et al. 2008), as well as employment in mine restoration, land remediation and associated research and development, which is mostly government funded (Table 1). These two industries (tourism and environmental repair) are in fact dependent on each other. Given safe access to mined areas requires remediation/restoration, whilst the high expense of remediation/restoration is justified because of the economic stimulus provided by tourism.

2.3 China

The number of abandoned mines in China is largely unknown and difficult to quantify but is likely to be huge due to the sheer exploitation of natural resources for energy production and raw materials for the development of the national economy. Consequently, this has resulted in the destruction of land and ecological environment, land subsidence, and pollution of soil and water resources (Zhang et al 2018).

Mining is a very large industry in China varying from small-scale workings by local villagers and small landholders to large open-pit mines by national or private companies (with over 8000 national and 230,000 private companies involved in mining; Venkateswarlu et al. 2016). This level of mining has created over 200,000 km2 of derelict land from metalliferous mines alone that has generated about 3.2 million ha of wasteland, and this figure is increasing at a rate of 46,700 ha per year (Li 2006). Some 370,000 ha of agricultural land has been lost in recent years due to mining (Li 2006).

China is the largest producer and consumer of coal globally, however many of their large traditional reserves in north-east China are now exhausted resulting in many mines being closed over the last decade or so, with most new mines now opening in western parts of China. In coal–rich regions of north-eastern China, such as Shanxi Province (which has 62,000 km2 of coal reserves, covering 40% of the area), coal mining and energy production is the main industry and source of tax revenue, employing many millions of people. This area is increasingly experiencing mine closures, many of which are abandoned, as larger deposits are exhausted and economic downturns combined with changes to government energy policy has resulted in many smaller mines closing (Cao 2017). In the case of Shanxi Province some 120 km2 of mining legacy landscapes can now be found (Yang et al. 2018). These landscapes often comprise large numbers (many hundreds) of small mine pits within relatively proximity to each other, many of which were worked by local villagers or small private firms, but now abandoned. In some areas, major government work programs and/or local community action has been implemented to rehabilitate these legacy sites and to contain pollutants. However, many others remain abandoned and continue to be polluting, or are unsafe due to subsidence, methane release and fire risks (Kuenzer et al. 2007; Hu et al. 2015). There is an also serious environmental problem associated with mine waste dumps and spoils being a major part of the post-mining landscape (Bain et al. 2010). The economic redevelopment and transformation of these areas is lagging (Yang et al. 2018). Examples of new industries being widely considered include agriculture and plantation forestry. However, given the scale and type of mining in many of these regions there are often major residual environmental impacts to be ameliorated and managed before these economic and land use transitions can take place (Bian et al. 2010). At some localities in Shanxi Province coal mining has been so intensive that land subsidence is now a serious issue and can be so bad that people have been evacuated to new areas as their houses and villages have become too unsafe to live in (Stanway 2016).

The economic and land use transitions being experienced in these major mining regions of China is demonstrated in a study of the Mengjiagou area of Shanxi Province by Yang et al. (2018). They showed, via remote sensing and indicators of economic activity, that the area has experienced profound fluctuations in land use and economy over a relatively short period from being mostly agriculture in 1980s (79% of land use and 62% of income) to being coal dependent in the next two decades (42% of land use and majority of income now from land leasing and coal mining labour). With the widespread closure of mines from 2010 the area is currently in a poverty trap having experienced massive drops in incomes and productivity (with agriculture land now only 9% of the area). As the land is mostly owned by local villagers and the mining companies were mostly local co-operatives, there is vested collective interest in returning the land to some sort of productivity, with eco-agriculture currently being favoured (Yang et al. 2018).

2.4 United States of America

In 2008 it was identified that there were approximately 550,000 abandoned mines in the USA, which have generated a staggering 45 billion tonnes of waste and other environmental management issues, including the generation of tailings that range in pH values from extremely low 2–7 pH. Such a range in pH results in challenges in relation to revegetation due highly acidic soils amongst other issues (Mendez et al. 2008).

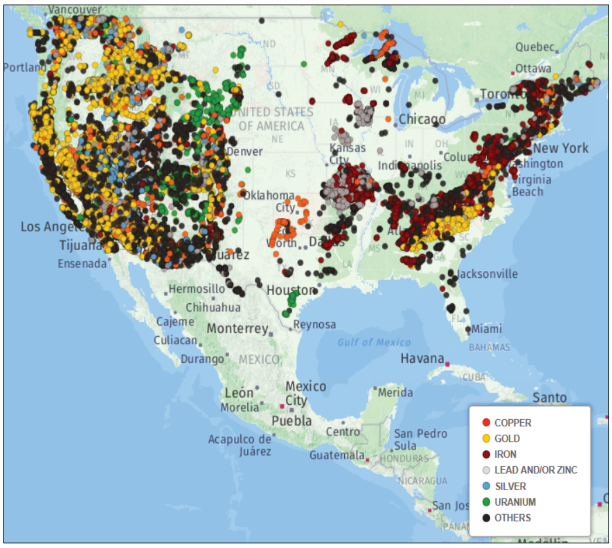

Figure 4 Inactive mines within the USA (adapted from https://davidmanthos.carto.com/viz/9e48164c-45da-11e5-bcf9-0e0c41326911/embed_map)

Whilst Figure 4 shows the spatial location of 'inactive' mines within the USA, the highest producing states are noted to be (in order from lowest to highest) Minnesota, which produced vast amounts of iron ore, California, boron production, Texas, Arizona producing copper and molybdenum and Nevada gold production (U.S. Geological Survey 2017; Manthos 2018). Given the high production of minerals in Nevada and Arizona these states were chosen as our Case Studies.

Gold was discovered in California in 1849, which sparked a massive gold rush resulting in an influx of miners throughout Sierra Nevada. During this period gold was mined using hydraulic mining of placer deposits. This type of mining is defined as 'The extraction of heavy mineral from a placer deposit by concentration in running water. It includes ground sluicing, panning, shoveling gravel into a sluice, scraping by power scraper and excavation by dragline, dredge or other mechanized equipment' (The Hudson Institute of Mineralogy 2019).

It is also worth noting that elemental mercury was also used and associated with gold mining in Sierra Nevada in 1849 which continued for more than 30 years whereby gravels were washed in sluices to which mercury is added as an amalgam that collects in the bottom of the sluices. However, this mining method was replaced by the hydraulic gold-mining technique in 1852 where it was halted by a court order 1884 (Alpers et al. 2014; Bouse et al. 2010).

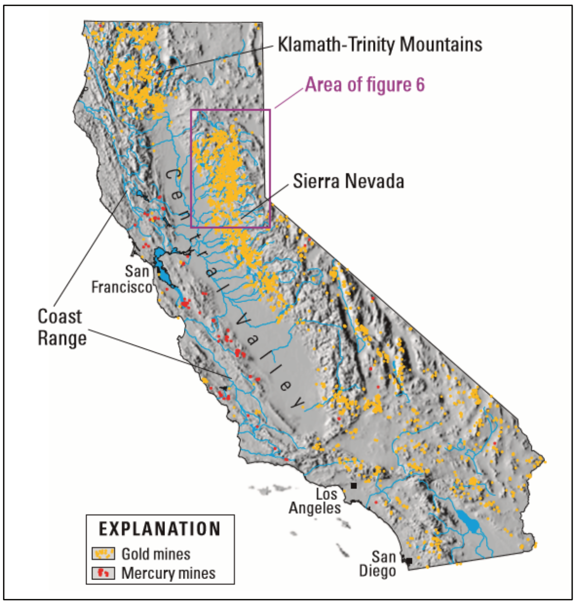

Figure 5 Location of former gold and mercury mines within California (adapted from U.S. Geological Survey (USGS) 2016)

The proliferation of abandoned gold mines in the USA has resulted in significant environmental issues including surface instability, landslides, subsidence, soil erosion, water pollution, and wildlife habitat loss. Acid Mine Drainage and the dispersion of contaminated tailings into the receiving environment are noteworthy risks that have the potential of manifesting themselves for decades (Peltz and Harley 2016). This issue is of concern when mines are located high in the catchment or watershed where sediments laden with heavy metals become mobile and enter downstream ecological systems resulting in erosion and environmental threats to humans and aquatic systems (Lecce and Pavlowsky 2014; USGS 2016 (Figure 5).

3 Discussion and conclusions

3.1 Environmental issues

The environmental impacts of abandoned mines are wide ranging (Table 1), but relatively well studied and understood, and generally there is an accepted approach for the management or mitigation of these impacts, although there are perhaps fewer documented examples of their successful implementation. Impacts mainly stem from waste disposal facilities (tailings dams and waste rock dumps etc.) which continue to release pollutants in the surrounding environment (land, water and air), or can experience catastrophic collapse (Table 1).

3.2 Application of unmanned aerial vehicles

The proliferation and global uptake in relation to the use of UAV is largely driven by the availability of sophisticated systems, including fixed-wing, flapping wing, rotary-wing, tilt-rotor, ducted fan, helicopter, ornithopter, and unconventional types allowing a wider spectrum of uses from civilian to military applications (Shahmoradi et al 2020). Such systems are also equipped with highly accurate electromagnetic spectrum, and geophysical instrumentation (Park and Choi 2020). Whilst our paper has investigated a multiplicity of UAV applications and situations within our case study regions (Table 2). Our research clearly shows that the application of UAVs to remotely monitor the social and environmental issues associated with abandoned mines is a safe, cost effective, efficient and accurate when examining these matters in finer detail and scale.

Table 1 Reported or inferred environmental legacies of abandoned mines emerging from case studies and other literature, together with typical solutions and strategies for management

Impact Type	Documented impacts	General Solutions and Management	References
Surface Water Pollution	Leaking tailings dams; pollution from disposal of tailings into major waterbodies with metals and other pollutants persisting in sediments,	Tailings removal and treatment; improved containment; revegetation of tailings; land remediation	Mhlongoa and Amponsah-Dacosta 2015, Doupé, and Lymbery 2005
Groundwater Pollution	Contaminated groundwater which may become unfit for irrigation or drinking	Clay or other barriers at base on mines	Moyé et al 2017; Zhou et al 2018
Groundwater level changes	Groundwater filling voids and creating drawdown of surrounding water sources	Surface water management; aquifer recharge	Pujades et al 2016; Wang et al 2016
Land Contamination	Tailings and pollutants transported via wind and water from tailings; crops contaminated by heavy metals are not suitable for human consumption	Soil remediation, phytoremediation	Venkateswarlu et al 2016; Wahsha et al 2016
Catastrophic failures	Tailings dam wall collapses and breaches	Reinforcement, revegetation and monitoring using remote sensing technologies such as UAS and UAV platforms	Mayes and Javis 2016; Iannacone et al 2018; Padro et al 2018
Soil Erosion, Subsidence, Landslides	Wind and water erosion of highly disturbed area; unconsolidated tailings and waste dumps; steep mine pit slopes	Revegetation, remediation and monitoring using remote sensing technologies such as UAS and UAV platforms	Marschalko et al 2015; Cigna et al 2017; Padro et al 2019
Air Pollution	Dust from tailings is contaminated with heavy metals	Capping, revegetation	Doumas et al 2018; Asif and Chen 2018
Radioactivity	Persistent Ur and other radioactive isotopes	Depopulation and monitoring using remote sensing technologies such as UAS and UAV platforms	Carvalho et al 2016; Paiva et al 2019; Padro et al 2018 and Padro et al 2019; Martin et al 2016
Ecological, Biodiversity	Soil/land disturbance promoting invasive species; infrastructure a conduit for invasive species; fragmentation of habitats	Pest plant and animal control	Giam et al 2018; Zhang et al 2018

Human Health, Safety	Heavy metal exposure via dust and water consumption; accidental falls	Access control	Mpode Ngole-Jeme and Fantke 2017; Wcisło etal 2016
Social Economic	Population declines; loss of jobs, main industries	Alternative industries, recreation and tourism opportunities; restoration and remediation industry	Mhlongoa and Amponsah-Dacosta 2015; Lei et al 2016
Others	Coal fires; methane emissions	Capping	Wang et al 2017; Li et al 2017

Table 2 Further examples and applications of unmanned aerial vehicle (UAV) technologies within each case study area

Region	Land use(s)	Technology	Associated social and environmental considerations	Data Interpretation	References
Australia	Fire management; Costal management; Agriculture; Mining; Marine habitat	UAV Remote sensing, UAV LiDAR; thermal infrared (TIR) imagery; multispectral (MS) imagery; e Scan Eagle UAV, carrying a digital SLR camera	Impacts of fire associated with rehabilitated mine lands. Damage to costal dune systems and infrastructures Water losses caused by drought and impacts to food crops; Anthropogenic impacts	Fire severity on forest ecological systems; Erosion, vegetation monitoring; Evapotranspiration; Assessing abundance, distribution, habitat of marine fauna	McKenna et al 2017; Drummond et al 2015; Park et al 2021; Hodgson et al 2017
European Union	Forestry; Forest ecological functions and services; Dam construction; Geological surveys	UAV equipped with RGB thermal cameras, temperature sensors, and communication modules; Convolutional neural networks (CNN); High Resolution Imagery; UAV photogrammetry and 3D mapping; Hi-Target Differential Global Positioning System (DGPS); RGB, Multispectral, NIR images – 3-D	Impacts of wildfires on native and plantations, human losses and ecological systems; Insect damage, forest degradation; Dam construction and failures loss of human life and properties; Safer technology due to steep mountainous terrain	Frequency and severity fires; Environmental impacts of four-eyed fir bark beetle to forest species; Geological mapping and data interpretation	Al-Kaff et al 2020; Safonova et al 2019; Ajayi and Palmer 2018; Piras et al 2017
China	Abandoned coal mining operations; Agriculture; Tourism and aquaculture; Multiplicity of a buildings and architectures	Interferometric synthetic aperture radar (ISAR); MODIS - high resolution; UAV - photogrammetry –high resolution & 3-D imagery	Atmospheric, soil and water pollution; sterilisation of ore bodies; Water quality – cyanobacteria; Flooding caused by monsoons	Fire causation and monitoring; Impact of fast-growing macroalgae – distribution; Riverbank monitoring	He et al 2020; Xu et al 2017; Boonpook et al 2018

			subsequent to buildings along river foreshore		
USA	Buildings; bridges; Transport routes & other infrastructures; Nuclear facilities, Costal management	Ardu Hexacopter (Ardu) and a Spider Quadcopter Done technology, Radar; Electro-optical; Radioemission; Magnetic detection systems; fixed-wing UAV equipped with a multispectral digital camera for SfM multirotor UAV equipped with a Light Detection and Ranging (LiDAR)	Human safety due to failures of infrastructures; Nuclear security; Wind erosion	Monitoring thickness of steel, wood, concrete to determine cracking tolerances; Monitoring unauthorised access; Sediment transport and mobility of migrating dunes	Ryan et al 2020; Duque et al 2018; Solodov et al 2018; Solazzo et al 2018

3.3 Socio-economic issues

It is fair to conclude that ongoing socio-economic impacts following mine closure are generally given less consideration than the residual impacts on the aquatic and terrestrial environments. Through the case studies we have demonstrated that a range of post-closure land use options can reinvigorate and even transform the local economy after mining. Some of these options include:

- Tourism, especially mining heritage tourism (Cole 2004);
- Recreation, with infrastructure left after mining potentially usable (e.g., tracks, facilities, dams);
- Conservation, especially where lands surrounding mining activity had been off limits to humans;
- Agriculture, especially where agriculture was previous land use before mining;
- Plantation forestry.

However, it is also clear from this review that redevelopment opportunities can be constrained by environmental legacies and associated ongoing risks and requires remediation and restoration actions to be undertaken to ensure a safe and productive environment (Cole 2004). It is important such co-dependencies (between restoration/rehabilitation and socio-economic development) are recognised when planning post-mine options and those synergies between them are explored and utilised. Mine site rehabilitation/restoration is an important industry in its own right employing many people in numerous areas from research and development through to on the ground action and ongoing monitoring. However, this activity is often under-resourced and for abandoned mines money is typically needed from government (although bonds and other industry contribution schemes are important here). The implementation of remote sensing technologies and the deployment of Unmanned Aerial Vehicles and Unmanned Aerial Systems is a technology that is showing promising results when it comes to gathering baseline data in challenging and high-risk environments (Deng 2021).

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