

Applying monitoring data to measure and improve rehabilitation performance at four mine sites in the Pilbara region of Western Australia

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Abstract

Atlas Iron Pty Ltd (Atlas) rehabilitated four iron ore projects in the Pilbara region of Western Australia between 2013 and 2017. Rehabilitation works at each project have involved reshaping and revegetation works on waste rock landforms (WRLs), construction of abandonment bunds and removal of non-essential infrastructure. Atlas has set a target to demonstrate the achievement of completion criteria for all WRLs within 10 years of completing the rehabilitation works. This paper explores the temporal trends in rehabilitation monitoring data across the four projects and how the monitoring data has been used to inform remedial works that have been undertaken to improve rehabilitation performance.

Uncontrolled surface water/erosion and poor revegetation were identified as key closure risks for the projects and, as such, the emphasis in this paper is on vegetation and erosion performance on the rehabilitated WRLs. Vegetation performance has been assessed using traditional methods including plots and transects, along with visual spectrum and multispectral imagery. Erosion performance has been assessed using orthophoto and digital elevation model (DEM) data.

Rehabilitation performance has been compared against the completion criteria, which have been agreed upon with regulators and other stakeholders and have been derived using data collected from a combination of rehabilitated areas and natural analogue areas.

Rehabilitation performance has been variable across the projects but has generally been successful, and multiple rehabilitated areas are already meeting the agreed completion criteria. The monitoring data has indicated that a small number of rehabilitated areas are unlikely to meet the completion criteria. Atlas uses the annual monitoring data to determine their priorities for remedial works in rehabilitated areas. Remedial works have consisted of implementing drainage controls, stabilising slopes and repairing erosion gullies, reseeding, weed management, and constructing fences to exclude livestock.

Keywords: *rehabilitation, completion criteria, monitoring, erosion, vegetation, remedial works*

1 Introduction

Atlas Iron Pty Ltd (Atlas) is an Australian owned iron ore company that operates in the Pilbara region of Western Australia. Atlas has constructed, operated and rehabilitated four projects including the Pardoo, Mt Dove, Abydos and Wodgina iron ore projects (Figure 1). Rehabilitation works were completed at Pardoo and Mt Dove in 2014, and at Abydos and Wodgina in 2017. Rehabilitation works at each project included waste rock landform (WRL) reshaping, application of rock armour (where required) and topsoil (where available), construction of drainage controls, contour ripping and seeding.

This paper explores the temporal trends in rehabilitation monitoring data across the four projects and looks at rehabilitation performance against the agreed completion criteria, and discusses how the monitoring data has been used to inform remedial works that have been undertaken to improve rehabilitation performance.



Figure 1 Location of Atlas' rehabilitated projects

2 Rehabilitation works

The rehabilitation works that were undertaken for each project WRL are described in Table 1. Detailed closure designs were developed for each WRL considering their as-constructed geometry, the requirement to manage drainage and minimise erosion, and the erosional stability properties of the waste rock. The closure designs were approved, and work packs developed and implemented for each WRL.

WRL slopes were reprofiled to angles between 15° and 20° and mapped exposures of low stability waste rock and zones prone to flooding were armoured with durable rock. Back-sloping berms were established for relevant WRLs. Drainage controls were constructed on and around WRLs including back-sloping crest bunds, retention cells and bunds, and perimeter toe bunds. Whilst there was an overall topsoil deficit across the projects, topsoil was applied to rehabilitated areas where it was available. All surfaces were ripped on the contour and seeded with native seed at a rate of 6–10 kg/ha.

Table 1 Rehabilitation works undertaken at each WRL

Closure tasks	Trigg WRL	Metlams WRL	Leighlons WRL	Alice WRL	Bobby WRL	Chloe WRL	Emma WRL	South limb WRL	South limb West WRL	Mt dove WRL	Anson WRL	Hercules WRL
Rehabilitation completed	2017	2017	2017	2014	2014	2014	2014	2014	2014	2014	2017	2017
Project	Abydos	Abydos	Abydos	Pardoo	Pardoo	Pardoo	Pardoo	Pardoo	Pardoo	Mt Dove	Wodgina	Wodgina
Re-profile slopes	✓ (20°)	✓ (18°)	✓ (17°)	✓ (20°)	✓ (18°)	✓ (17°)	✓ (18°)	✓ (18°)	✓ (18°)	✓ (15°)	✓ (18°)	✓ (18°)
Establish back-sloping berms	✓	NA	NA	NA	NA	NA	NA	✓	NA	NA	✓	✓
Apply rock armour	✓	NA	NA	✓	✓	✓	✓	✓	NA	✗	✓	✓
Establish drainage controls	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✗ / ✓	✓
Apply soil	✗ / ✓	✗ / ✓	✗	✗ / ✓	✓	✓	✓	✓	✓	✓	✗ / ✓	✗ / ✓
Contour rip	✗ / ✓	✗ / ✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Spread seed	✗ / ✓	✗ / ✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓

NA – not applicable ✓ – complete ✗ – not completed ✗ / ✓ – not completed on all surfaces

There were some exceptions where rehabilitation works did not align with the specified workpacks:

- Top surface drainage controls were not completed for Trigg and Mettams WRLs, but these will be completed during 2022.
- Contour ripping for the Leightons and Anson WRLs was not always on contour.
- Gravel was not applied to the required sections of the Mt Dove WRL.
- The Hercules WRL was never tipped out to its original design and there were limitations in the rehabilitation design. Some sections of the Hercules WRL remained at the as-constructed geometry.
- To maintain access to the area, upstream catchments of the Anson WRL were not closed off.

3 Climate

Environmental factors, such as climate, greatly influence the success of rehabilitation, particularly in arid areas such as the Pilbara (Commonwealth of Australia 2016).

Rehabilitation works at Pardoo and Mt Dove were completed in 2014. Rainfall was approximately 100 mm and 300 mm below average in 2015 and 2016 respectively (Figure 2). Rehabilitation works at Abydos and Wodgina were completed in 2017. Rainfall was slightly above average in 2018, slightly below average in 2019, and was nearly 200 mm above average in 2020.

Data presented in Figure 2 was collected from Marble Bar station which is located central to all four projects. At Marble Bar, annual average rainfall is approximately 390 mm as reported by the Australian Government Bureau of Meteorology (BOM 2022).

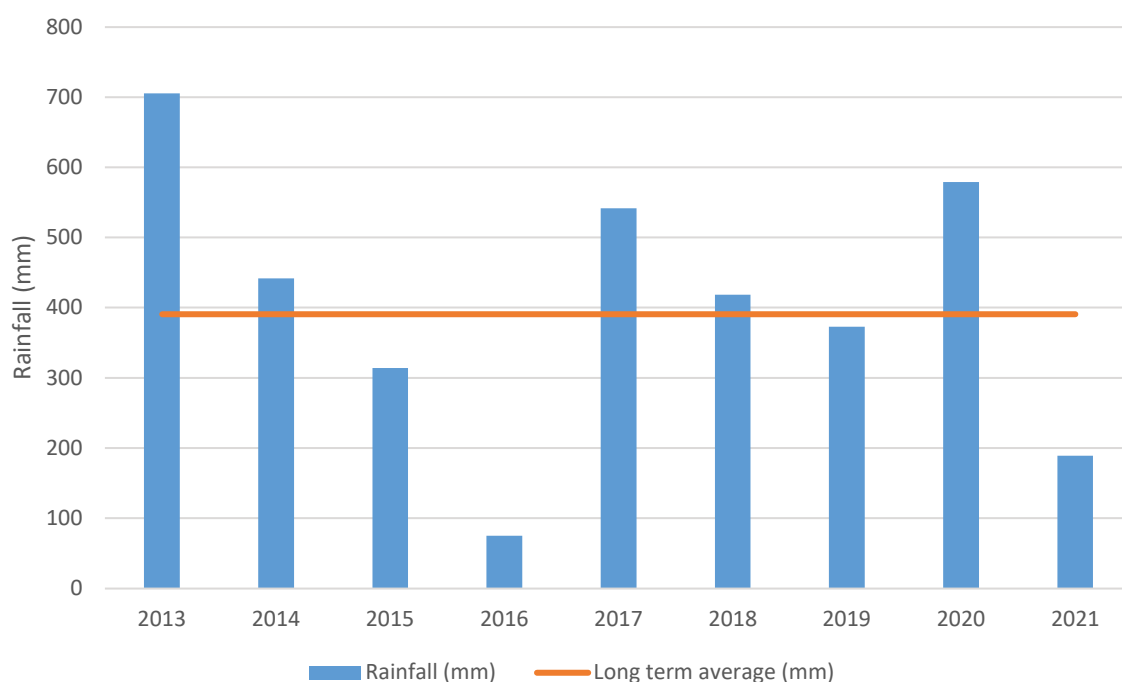


Figure 2 Annual rainfall totals recorded at the Marble Bar weather station from 2013 to 2021

4 Completion criteria

Closure performance data for all rehabilitated WRLs is measured against completion criteria and is reported to relevant stakeholders. This data will be used as evidence to support tenement relinquishment or partial surrender of rehabilitated areas. The completion criteria were agreed to with regulators and other stakeholders, and approved by the Western Australian Department of Mines, Industry Regulation and Safety in each project's mine closure plan (MCP).

The outcomes, criteria and standards required to measure closure performance relate to each other as follows:

- Outcomes describe the intent of the mine closure program.
- Criteria describe specific elements that can be measured or certified to have occurred and that are critical to achieving the outcome.
- Criteria may have standards which are either an agreed value that is measurable and is regarded as the minimum that must be achieved, or a certification that closure works comply with an agreed design.

Atlas aims to deliver the required outcomes by meeting all completion criteria for the WRLs within 10 years of completing the rehabilitation works.

While each project has specific closure outcomes for vegetation, they generally relate to achieving a self-sustaining native vegetation community. This vegetation outcome is supported by several leading and lagging criteria. The leading criteria typically relate to revegetation being implemented in accordance with an approved design and representative taxa from nearby vegetation communities being used in the seed mix. Lagging criteria have been developed for plant cover, species richness, and weed cover; these parameters are required to meet an agreed standard. Site-specific standards for each project are presented in Table 2. Vegetation standards have been calculated using data from the top performing rehabilitation sites and from natural analogue site data. Atlas continues to update the vegetation standards for each project as monitoring data is collected and in consideration of recent climatic events (i.e. fire, drought, flooding, etc.) and changes in vegetation structure.

Table 2 Agreed vegetation completion criteria standards for each project

Project	Plant cover	Species richness (no. species per 50 × 50 m plot)	Weed cover
Pardoo	35%	11 species	10%
Mt Dove	23%	16 species	10%
Abydos	22%	23 species	20%
Wodgina	26%	15 species	10%

Each project also has specific outcomes, criteria and standards that relate to surface water management and erosion (sourced from the approved MCPs). The outcome for surface water for all WRLs states that 'uncontrolled surface water flows and impacts to surface water will be minimised'. This outcome is supported by leading and lagging criteria. The leading criteria typically relate to WRLs being constructed in accordance with their closure design and surface water controls being constructed and operating as they were designed. The lagging criterion for all projects states that 'erosion rates on the WRLs will stabilise'. Standards for this lagging criterion have been calculated using site-specific rehabilitation data and are presented in Table 3.

Standards for surface water for all WRLs have been updated recently with the shift from traditional transect erosion monitoring to using unmanned aerial vehicles (UAV). Orthophoto and digital elevation model (DEM) data collected for all WRLs via UAVs since 2018 has been used to develop an inventory of all gullies for each WRL. The position, length, width, depth and volume of each gully is recorded, and every gully is classified as

green, amber or red. While green and amber gullies are closely monitored over time, red gullies represent features which could threaten WRL stability and/or surface drainage control and require remediation. Red gullies, if identified, have a management plan developed that typically describes the required remediation activities.

For Pardoo and Mt Dove, the standard is that no red gullies will be present on the WRL (Table 3). At Pardoo, a 'rate of change' standard has been calculated and is also used to demonstrate that erosion rates have stabilised. For Abydos and Wodgina, standards have been developed around an acceptable rate of change in erosion over time. While they have been presented in this paper, these standards are currently under review and will be refined once further data is collected.

Table 3 Surface water completion criterion and standards for each project

Project	Criterion	Standards
Pardoo	Erosion rates stabilise	No red gullies are reported Change in gully volume between assessments should be less than 10 m ³ /ha over a three-year period
Mt Dove	Erosion rates stabilise	No red gullies are reported
Abydos	Erosion rates stabilise	The change in the proportion of the bank eroded measured annually will be less than 5% over three monitoring events
Wodgina	Erosion rates stabilise	The average annual change in proportion of bank erosion will be less than 5% over three monitoring events

5 Monitoring data

Vegetation and erosion monitoring data have been collected by specialist consultants at each project since rehabilitation works were completed. Vegetation data has been collected from five monitoring events at Pardoo and Mt Dove, three monitoring events at Wodgina, and two monitoring events at Abydos. UAV erosion data has been collected from three monitoring events at all projects except Mt Dove where data has only been collected from two monitoring events. The monitoring events include (but are not limited to) an assessment of perennial plant cover, perennial species richness, the presence of seedlings, the occurrence of weeds, dimensions, and count of erosion gullies.

5.1 Vegetation

Perennial plant cover, species richness and weed cover data from each project are presented in this section, along with the range of site-specific completion criterion standards.

Perennial plant cover data is presented in Figure 3 along with the range of standards for each project. Plant cover has increased over time at each project. Plant cover at Pardoo is outperforming Mt Dove, which has a similar age, and is exceeding the calculated plant cover standard. At Wodgina, the plant cover in year four fell within the range of values recorded from Pardoo. For Abydos, plant cover was similar at year two to Pardoo, indicating that plant cover may follow a similar trajectory.

The development of perennial plant cover at Mt Dove has been slow and plant cover has remained low during the first five years of monitoring (Figure 3). Data from the year seven monitoring event has shown a considerable increase at Mt Dove, with average plant cover increasing to slightly below the standard. Revegetation performance at Mt Dove has been impaired by stock grazing.

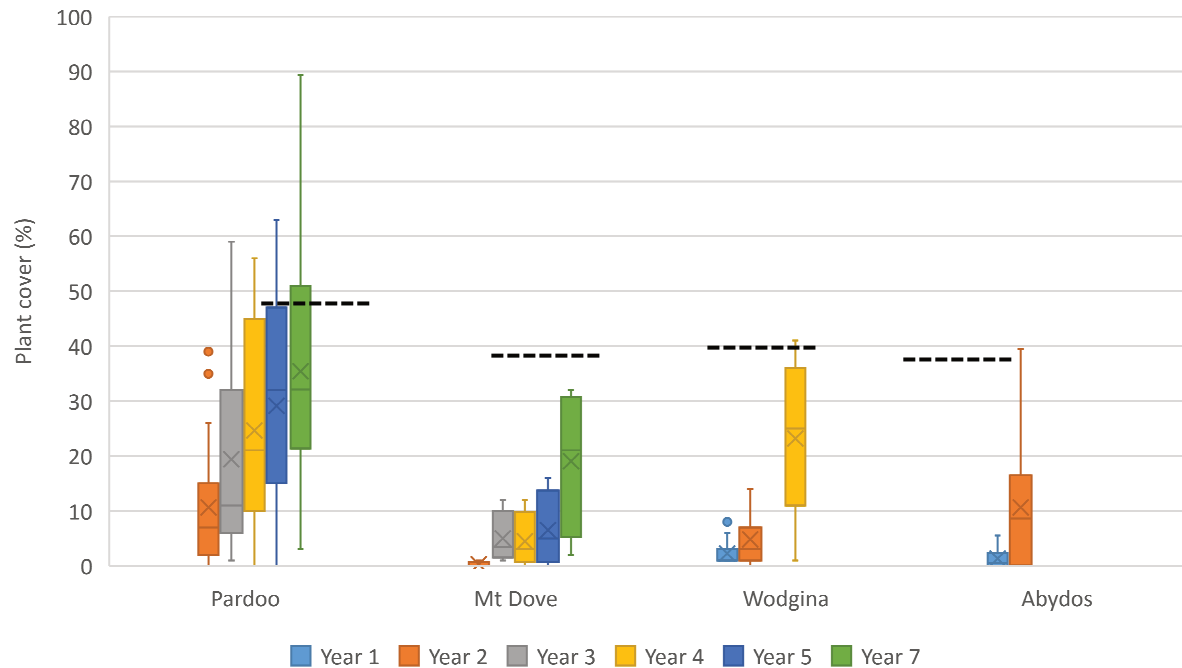


Figure 3 Box plot of plant cover (%) at each project by age of rehabilitation against the site-specific project standard (represented by the black dotted line)

Species richness data is presented in Figure 4 along with the range of standards for each project. Changes in species richness over time has occurred at each project.

At Pardoo, species richness has progressively increased until year four, reached its maximum and has shown a decreasing trend over the last two monitoring events (Figure 4). Species richness at Mt Dove continues to increase over time, while at Wodgina species richness increased between years one and two but decreased in year four. At Abydos, species richness decreased between year one and two but was typically much higher than the other projects (Figure 4).

Species richness across the WRLs has likely been influenced by the application of different thicknesses of topsoil, variations in topsoil quality, different seeding rates, quality of seed, number of species used in the seed mix, ability of seed to break dormancy and the climatic conditions experienced since the rehabilitation works were completed. There are no clear trends in data across the projects. While the seed mixes for Pardoo and Mt Dove contained 35 species each (Atlas Iron 2013; Mine Earth 2013), the seed mixes for Abydos and Wodgina only contained 25 species (Woodman Environmental 2019a, 2019b). At Pardoo, Mt Dove and Abydos, WRLs were seeded at a rate of 10kg/ha (Atlas Iron 2013; Mine Earth 2013) and the seeding rate at Wodgina was 8 kg/ha (Mine Earth 2020). Given the large number of species present at Abydos, it is likely that the topsoil used on the WRLs contained a large seed bank given that fewer species were used in the seed mix. The topsoil stockpiles at Abydos, supported a considerable vegetation community prior to use in rehabilitation activities.

Species richness standards have been met at all projects (Figure 4).

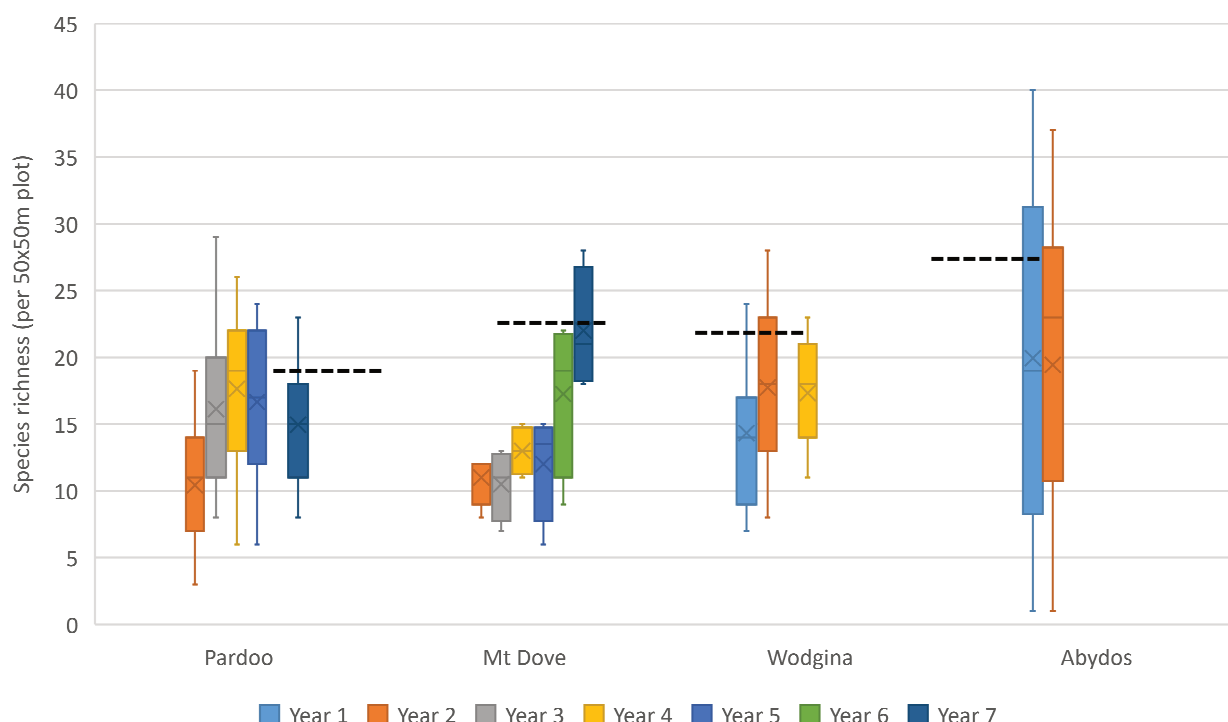


Figure 4 Box plot of species richness (no. species per 50 × 50 m plot) at each of the projects by age of rehabilitation against the site-specific project standard (represented by the black dotted line)

Weed cover at Pardoo was typically low and below the 10% standard (Figure 5). A few outliers at Pardoo were recorded and these were from sites where topsoil was scarce. Weed cover had increased considerably in the most recent assessment and this was related to the occurrence of Kapok (*Aerva javanica*) on the Bobby WRL. This species has tended to dominate a small rocky section of the WRL which was reworked after the initial rehabilitation program to improve the trim and contour ripping on the final slope, which subsequently buried the topsoil in this area. Ongoing weed management has been implemented across all projects to manage weed populations.

Weed cover at Mt Dove was high and has shown a decreasing trend over time as native perennial plant cover has increased (Figure 5). The Mt Dove WRL was also dominated by Kapok (*Aerva javanica*). It is likely that the spread of weeds at Mt Dove is associated with stock grazing on the WRL. It is interesting to note that as weed cover on the Mt Dove WRL has decreased, species richness has increased (Figures 4 and 5).

Weed cover at Wodgina and Abydos has remained low and below the respective weed cover standards. Due to the high weed load recorded during the baseline study at Abydos (Woodman Environmental 2009), a weed cover standard of 20% was approved at that project. Given the low weed cover at Abydos, this standard could be readjusted to 10% to align with all other Atlas projects.

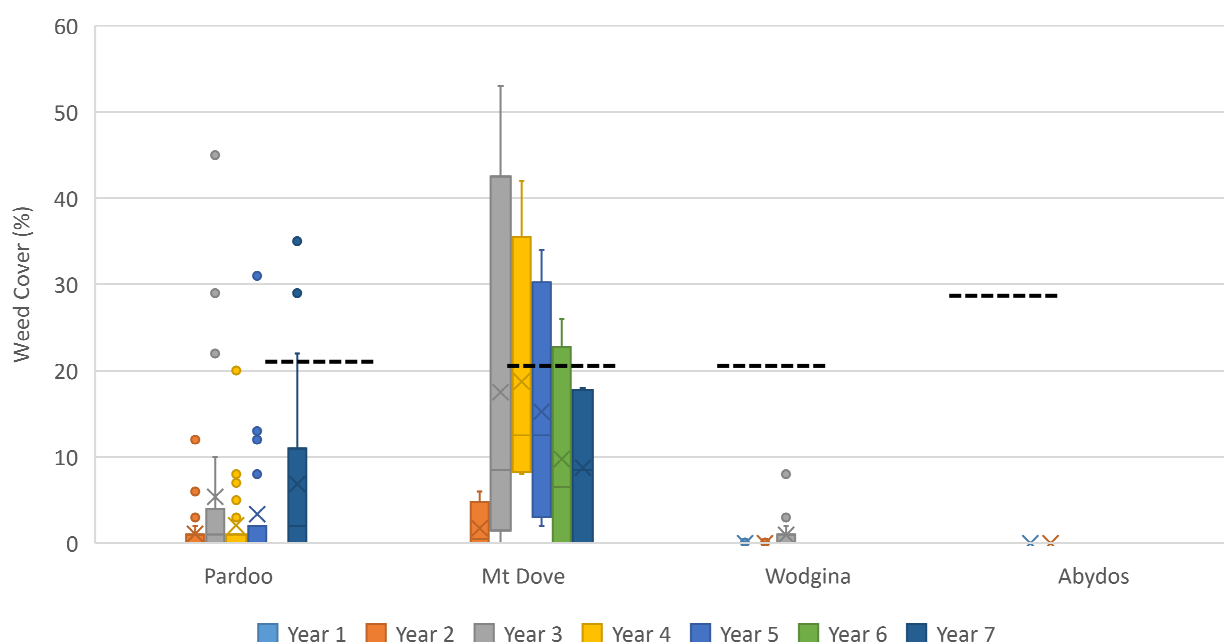


Figure 5 Box plot of weed cover (%) at each of the projects by age of rehabilitation against the site-specific project standard (represented by the black dotted line)

5.2 Erosion

The WRL completion criteria for erosion are focused around demonstrating that erosion rates have stabilised over time. Erosion monitoring for each WRL has included an assessment of the number and type of gullies as well as gully dimensions and volume. Temporal change in gully volume has also been used to demonstrate performance at most projects. This data is presented in this section, along with site-specific standards.

The number of red erosion gullies identified from the 2021 UAV monitoring events is presented in Table 4. Only a small number of gullies have been classified as red and pose a threat to WRL stability.

Table 4 Number of erosion gullies recorded at each Project during the 2021 assessment

Project	Number of waste rock landforms	Batter surface area (hectares)	Number of red gullies
Pardoo	6	152.5	1
Mt Dove	1	3.6	3
Wodgina	2	45.73	5
Abydos	3	17.3	6

One red gully was recorded from the South Limb WRL at Pardoo (Table 4). This gully formed from ponding on a small mid-slope berm and failure of a crest bund (Figure 6). Remedial works are planned for this area during 2022 (see Section 6).

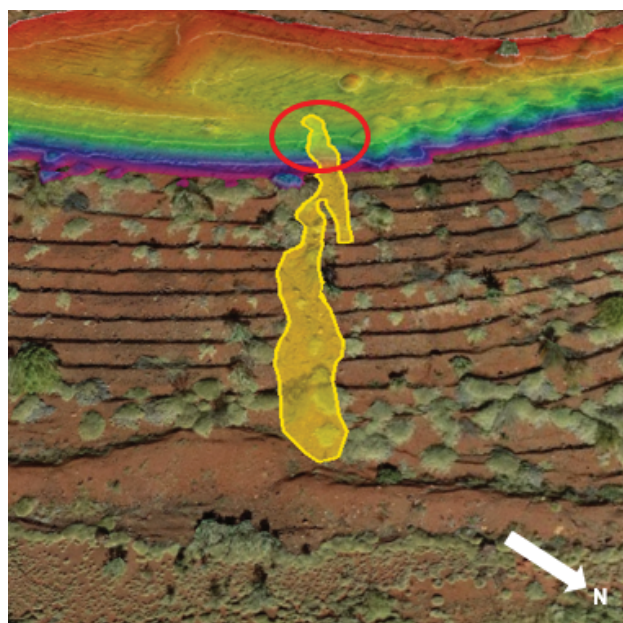


Figure 6 Elevation heat map of the Red gully at South Limb (Pardoo). Red circle indicates crest bund failure point

Three red gullies were identified on the Mt Dove WRL in 2021 (Table 4). All three gullies were located on the eastern WRL batter and were attributable to a combination of low stability materials, concentrated drainage along rip lines and impacts from cattle grazing (Figure 7). Remedial works were completed on this area in late 2021 and are described further in Section 6.

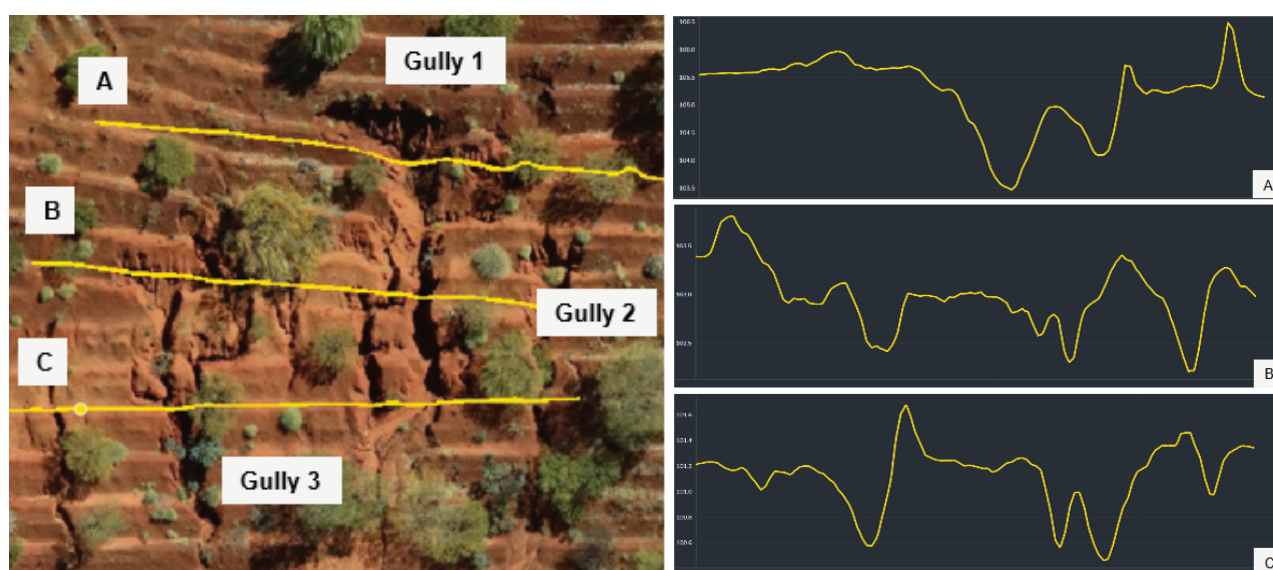


Figure 7 Three Red gullies present on the Mt Dove WRL. Cross-sections showing the elevation along rip lines (A, B and C) relative to batter surface

The WRL completion criteria for erosion have not yet been met at Pardoo and Mt Dove due to the presence of the red gullies.

Five red gullies were recorded at Wodgina in 2021 and were on the Anson WRL. Three of the red gullies on the Anson WRL formed due to substantial upstream catchments (including pit ramps) reporting to the WRL crest and onto downstream WRL slopes (Figure 8). These upstream catchments remained open during rehabilitation works to allow access to the project areas. The remaining two red gullies on the Anson WRL

formed due to concentrated runoff along a narrow forward-sloping berm. Remedial works were undertaken for all red gullies on the Anson WRL during late 2021 (see Section 6).

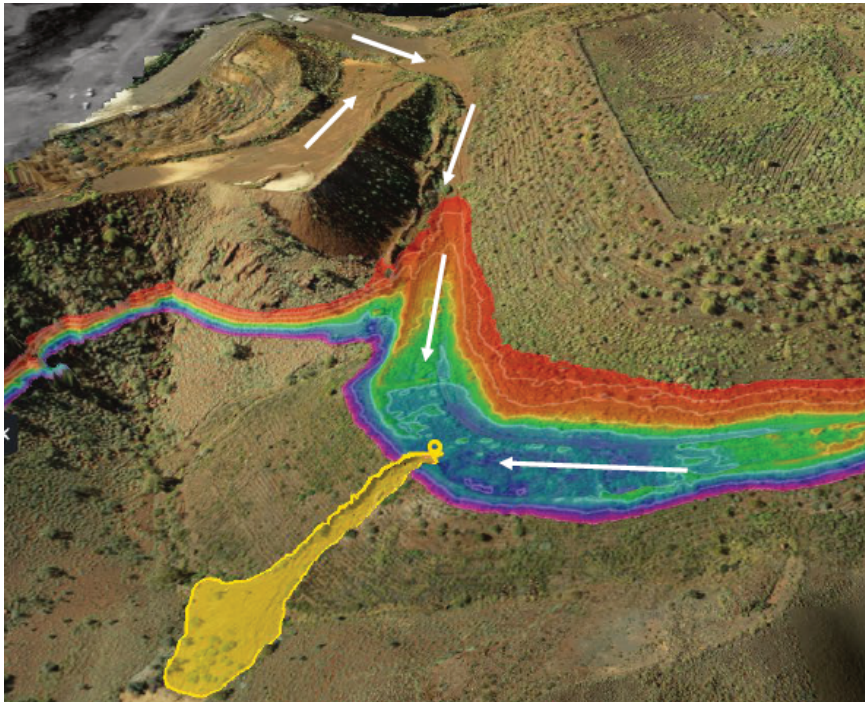


Figure 8 A Red gully on the Anson WRL being fed by an upstream catchment

Six red gullies were recorded at Abydos in 2021, three on the Leightons WRL, two on the Mettams WRL and one on the Trigg WRL. The red gullies on the Mettams and Trigg WRLs (Figure 9) have formed from concentrated drainage on the WRL top surfaces that has reported to downstream WRL slopes. Rehabilitation of the top surface (including the construction of drainage controls) of the Mettams and Trigg WRLs has not been undertaken and is scheduled for late 2022 (see Section 6).

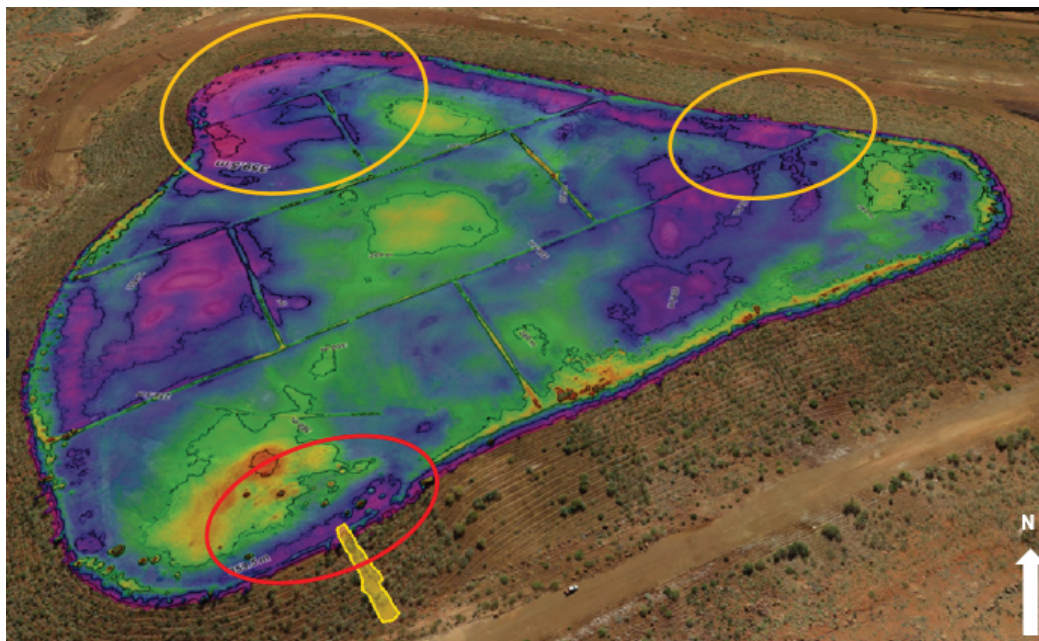


Figure 9 Trigg WRL top surface elevation. Circles indicates area of drainage concentration and potential (amber) and actual (red) overflow onto downstream batter

The temporal change in gully volume for each project is presented in Figure 10. Increases in gully volume between the 2020 and 2021 monitoring events was typically modest. Gully volume at Abydos is much greater than the other projects which is mainly due to the three red gullies on the Leightons WRL which had a combined volume of 250 m³/ha.

Progress towards meeting WRL completion criteria for erosion at each project is described in Table 5.

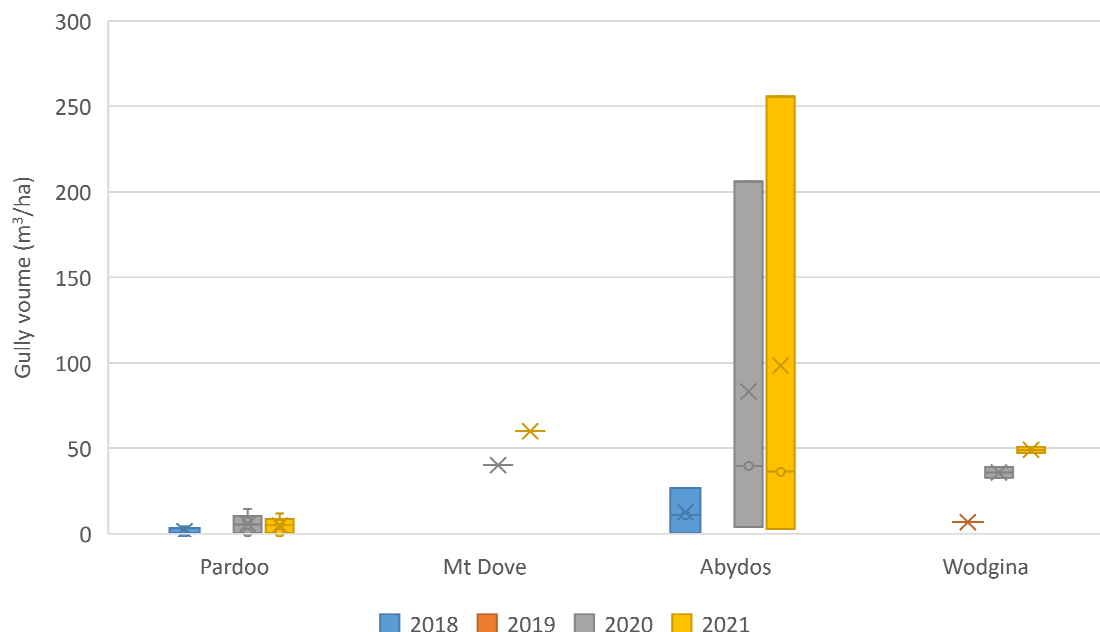


Figure 10 Box plot of gully volume (m³/ha) at each project

Table 5 Progress towards meeting WRL completion criteria standards for erosion at each project from the 2021 assessment

Project	Standards	Progress
Pardoo	No red gullies are reported	Achieved for all WRLs except for South Limb WRL. Remedial works on this WRL are planned for 2022
	Change in gully volume between assessments should be less than 10 m ³ /ha over a three-year period	Achieved for all WRLs
Mt Dove	No red gullies are reported	Not achieved. Note, remedial works were undertaken late in 2021 and all red gullies were remediated
Abydos	The change in the proportion of the bank eroded measured annually will be less than 5% over three monitoring events	Not achieved, however, remedial works are planned for 2022
Wodgina	The average annual change in proportion of bank erosion will be less than 5% over three monitoring events	Not achieved, however, remedial works are planned for 2022

6 Remedial works

Atlas has used the rehabilitation monitoring data to identify areas which are not performing in line with expectations and are unlikely to achieve the agreed completion criteria without intervention. Since the 2021 vegetation and erosion monitoring event (early–mid 2021), remedial works have been undertaken at Mt Dove and Wodgina (late 2021) to repair and rectify the causes of the red gullies. Further remedial works are planned for Pardoo and Abydos during 2022.

A description of the remedial works undertaken at Mt Dove and Wodgina, and planned for Pardoo and Abydos, is provided below.

Remedial works were undertaken during October 2021 on the eastern batter of the Mt Dove WRL to repair the three red gullies and rectify the causes of the gullies (Figure 7). These gullies had formed in this area due to a surface exposure of low stability material, drainage concentration along rip lines and cattle tracks. The remedial works involved stripping topsoil and vegetation from the eastern batter, shaping and trimming the batter and infilling the red gullies, stabilising the batter by sourcing and spreading rock armour (up to 1 m thick), respreading the topsoil and vegetation mulch. The eastern batter was ripped on the contour and hand seeded.

Remedial works were also completed on the ramp and top surface of the Mt Dove WRL to improve drainage controls by bolstering crest and cells bunds, and scalloping cells on the WRL ramp. The entire Mt Dove WRL was reseeded by hand and a fence was installed around the WRL to reduce the impacts from grazing livestock.

Remedial works were undertaken at Wodgina on the Anson WRL during October 2021. The aim was to repair all red gullies and rectify the causes of the gullies across three work areas; the northern, eastern and southern areas. These gullies formed as a result of surface water flow from upstream catchments which remained open to allow access to project areas.

Works in the northern area on the Anson WRL were focused on diverting runoff from a substantial upstream catchment (including a pit ramp) away from the WRL crest and downstream slope. The large red gully in this area was backfilled and back-sloping crest bunds were bolstered. The gully repair area and associated berm were shaped to a neat trim, contour ripped, and hand seeded.

In the eastern area on the Anson WRL, works were again focused on diverting runoff from a substantial upstream catchment (including a pit ramp) away from the WRL crest and downstream slope. The head of the red gully was backfilled and made safe, WRL crest bunds were bolstered and the repair area was shaped to a neat trim, contour ripped, and hand seeded.

Works in the southern area on the Anson WRL were undertaken to remove a narrow, forward-sloping mid-slope berm by cross-blading with a dozer to establish a single slope profile. The original closure design called for a single slope, however light vehicle access was required, and the resultant berm was not constructed as per the work pack instructions. The existing crest and cell bunds at either end of the repair area were bolstered to improve drainage controls. The repair area was then ripped on contour and seeded.

Remedial works will be undertaken at Abydos during 2022 to construct drainage controls and complete rehabilitation of the top surfaces of both the Mettams and Trigg WRLs and rectify the causes of the red gullies. This will involve constructing back-sloping crest bunds, levelling the top surfaces and establishing cells and cells bunds. Top surfaces will be ripped on the contour and seeded.

Minor remedial works will be undertaken at Pardoo during 2022 to repair the cause of the red gully on the South Limb WRL. Local material will be used to reform and stabilise the existing crest bund on the small mid-slope berm. The berm will be reconfigured such that water does not pond adjacent to the crest bund. A fence will also be constructed around the Bobby WRL during 2022 to reduce the impacts of livestock grazing on vegetation performance.

7 Conclusion

Atlas has successfully implemented rehabilitation works across four of their iron ore projects. Atlas' commitment to collecting robust monitoring data from rehabilitated WRLs has meant that progress towards meeting the agreed completion criteria can be demonstrated to regulators and other stakeholders. Where the monitoring data has indicated that the completion criterion may not be achieved without intervention, Atlas has implemented remedial works early to ensure successful long-term rehabilitation outcomes. To date the data indicates that most WRLs are on a trajectory to achieve the completion criteria within the 10-year window.

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