Chapter 1 Introduction and Background

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1.1 Introduction

Coal is one of Australia's significant export commodities. In 2006-7 alone, nearly 90 Megatons of black coal were exported, generating 21.8 billion dollars in export revenue (ABARE 2007). Although the majority of coal mines are open cut operations (Australian Coal Association 2007), open cut extraction techniques are only feasible where coal deposits occur relatively close to the surface. When open-cut coal mining is not feasible or ceases to be economically viable, underground longwall coal mining is seen as an increasingly viable alternative.

Agriculture is another important Australian commodity. During 2006-7, agricultural returns grossed some 34.4 billion dollars in total, with some 27.6 billion of that total coming from export revenues (ABARE 2007). Although open-cut coal mining and agricultural production are mutually exclusive activities, longwall coal mining and agriculture are not; it is possible for these activities to coexist on the same landscape.

In spite of the fact that longwall coal mining has been practiced in Europe since the 17th century (US Department of Energy 1985), very little is known about the impacts of longwall mining-induced subsidence (LMS) on agricultural production. In part, this may explain why longwall mining conjures up such strong opposition when mining companies propose underground operations within agricultural regions, as evidenced by the recent opposition to mining exploration in the Liverpool Plains area of New South Wales (NSW) (O'Brien 2008). The issue of longwall mining can be highly contentious with little agreement between opposing sides as to its possible ramifications.

1.2 Expansion of the Beltana Number 1 Mine

In 2003, Bulga Coal Management (BCM) submitted a development proposal to the NSW government. They proposed to extend their underground operations within the Hunter Valley to extract approximately 14 million tones of coal per annum by retreat longwall mining (Umwelt 2003). To fulfil their statutory obligations, BCM engaged an environmental consulting firm to undertake an environmental impact assessment (EIA) and to generate the resulting environmental impact statement (EIS). As the proposed extension would undercut several vineyards in the region, a viticulture expert was engaged to assess potential impacts of the proposed expansion.

The expert findings of the viticulturist Richard Smart were included as an Appendix within the EIS (Smart 2003). Although there are still no published studies examining the impacts of LMS on vineyards available in the literature, Smart (2003) concluded that the surface cracking induced by mining activities would be the impact most likely to affect vine health in the near term. However, he concluded that this potential impact would not necessarily be detrimental to the vines; a German study had suggested that surface cracking could help by stimulating root growth (Schulte-Karring 1987 as cited in Smart 2003).

To redress the lack of evidential information, Smart (2003) recommended that a project be undertaken to monitor the vineyards. He suggested that vines be monitored using standard viticulture biophysical measurements obtained at harvest and at pruning time. These should include collecting harvest descriptors of the number of bunches, yield, weight of 50 berries, sugar, acidity and pH and pruning measurements of cane number, pruning weight, and number of buds retained (Smart 2003, pp. 33-34). He also suggested that vines and rows be selected so as to ‘traverse across’ active longwall panels, progressing from areas of minimal subsidence through to areas of maximal subsidence (Smart 2003, p. 33).

1.3 Vineyard Monitoring Project

In response to both the Smart Report (2003) and pending development approval, Beltana Number 1 Mine and the University of New England (UNE) established a data collection project to facilitate monitoring of LMS impacts on the vineyards in the Broke-Fordwich region (Lamb 2003). As part of this process a Steering Committee was appointed to oversee the project. This committee was comprised of mining company representatives, academics, government regulators, and local vignerons.

The resulting data collection project was a multi-scale, multi-year endeavour designed to incorporate the recommendations of Smart (2003) as well as utilizing new techniques from the emerging field of precision viticulture. Although the basic field sampling methods proposed by Smart were standard techniques used in the viticulture industry, they are both time consuming and expensive to implement, precluding their wide scale use in all affected vineyard blocks across the region. However, remotely sensed data, both from space-based optical remote sensors and on-the-go ground based sensors, offered an unparallel ability to readily capture a larger data set quickly and in a cost effective manner (Frazier and Lamb, Pers. Comm.). More importantly, these technologies had previously demonstrated their potential in viticultural settings (e.g. Bramley 2001; Hall *et al.* 2003).

The first series of data were collected during the spring of 2003. From this time, data collection continued at regular intervals through to the project's conclusion in the summer of 2008.

1.4 Data Analysis Project

As the original monitoring project did not include provisions for analysing the collected data, in January 2007 a second project was initiated at the UNE. This second project sought to analyse the data collected throughout the monitoring project. The project's goal was to determine whether or not impacts associated with longwall mining-induced subsidence (LMS) were evident within the collected data. Using a subset of the collected data, this project investigated whether or not LMS had negatively impacted upon the productivity of the monitored vineyards within the Broke-Fordwich region. If such impacts were evident, the second aim of the project was to quantify the magnitude of these impacts on overall vineyard yields. This thesis is specifically concerned with the second aim of this project; namely the design and application of statistical analyses to components of the collected field data in order to ascertain the magnitude of impact of LMS on the undermined vineyards.

Most of the sampling methods employed during the monitoring phase of the project were not new; this phase borrowed heavily from the field of precision viticulture (PV – discussed further in Chapter 2). Whilst most of the data collected by PV techniques is of a quantitative nature, the data is often treated qualitatively. For instance, the work of Bramley and Hamilton (2004) and that of Bramley (2005) relied heavily on visual comparisons between several maps. Whilst such qualitative comparison can be instructive and useful for visually assessing similarities and differences across or between vineyard blocks, they are not sufficient when attempting to quantify the possible negative impacts associated with mining.

Because the detection ecological impacts are not the primary concern of such analyses, appropriate analytical method from other disciplines had to be identified. The identification of such methods comprised an integral part of this second project.

1.5 Thesis Structure and Outline

Does LMS impact upon viticultural productivity, vine yield in particular? If so, how, and what is the nature of LMS impacts? As previously noted, there is no previous literature that dealt with this specific issue. Addressing the question requires a multi-disciplinary approach, incorporating an understanding of mining subsidence, the annual grape vine phenological cycle, environmental impact assessment methods, as well as techniques from geographic information science and remote sensing.

To answer these questions, Chapter 2 reviews the subsidence literature to determine what previous case studies offer with respect to LMS impacts upon agriculture. The conceptual frameworks of these case studies are then extended to viticulture. In order to understand possible impact pathways Chapter 2 also provides relevant background information on grape vine phenological cycles. Finally, a brief review of environmental impact assessment techniques and methods is presented.

Chapter 3 outlines the methods utilized in the vineyard monitoring project, including the site description and a detailed explanation of the data collection framework developed by the Steering Committee. Furthermore, it also details the data processing and analytical methods employed. The results of this analysis are presented in Chapter 4. Chapter 5 discusses the results and conclusions and provides recommendations for monitoring projects.

First and foremost, this thesis is concerned with detecting environmental impacts in the monitored vineyards. Specifically, it seeks to determine whether or not LMS has impacted vine yields in a significant and systematic way. Whilst overall grape quality is as much a concern as yield, the drivers of grape quality are somewhat more ephemeral and difficult to assess. As such, concerns about the possible LMS impacts on grape quality are not addressed here.

Also included in Appendix B is a copy of a conference paper. This paper was presented at the 7th Triennial Conference of the Mine Subsidence Technical Society in 2007 at it contains a preliminary analysis of the monitoring data.

Chapter 2 Conceptual framework

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2.1 Introduction

As stated in Chapter 1, there are no previously reported cases in the literature where the potential impacts of LMS on viticulture have been studied. Hence, this chapter reviews the broader literature pertaining to the impacts of longwall mining-induced subsidence (LMS) on agriculture in general. To do so, it commences with an explanation of the longwall mining process itself, with particular attention given to the systematic creation of subsidence troughs and some of their relevant characteristics.

A series of four case studies are then reviewed. Although LMS is a subset of mining-induced subsidence (MS), its regular, periodic nature leaves a distinctive footprint on the overlying topography. Whilst all of the selected case studies did not always focus exclusively on LMS, each of them did explore the impacts of these LMS ‘footprints’ on agriculture in some way.

To better understand how yield in production viticulture systems might be impacted by LMS, a brief review of the phenological cycles of wine grape vines is then presented. Particular attention is paid to the phases of grape (berry) development, as these have particular relevance to the analysis presented in Chapter 4 and the ensuing discussion in Chapter 5. A targeted review of relevant precision viticulture practices is also included as background to the methodology presented in Chapter 3.

This chapter concludes with a brief review of relevant techniques and statistical methods for environmental monitoring. This review draws primarily from the field of environmental impact assessment. Although a thorough review of available methods is beyond the scope of this thesis, a short review is required for the critique and discussion presented in Chapter 5.

2.2 Longwall mining-induced subsidence

Longwall coal mining is classified as a caving method of underground mining (Kratzsch 1983, 1986). The removal of resources from below the earth’s surface creates underground voids and occurs with all forms of subterranean mining. When significant quantities of materials are removed, these voids can upset the stress balance of the overlying strata by increasing its exposure to gravitational forces. Eventually when this stress exceeds the ability of the overlying strata to support itself, it collapses inward, thereby filling the void left by mining. What separates longwall mining from other forms of underground mining, is that the process of subsidence occurs in a somewhat controlled manner in conjunction with the actual mining process (Singh 1992).

Longwall mining offers several advantages over traditional underground techniques, such as the ‘room and pillar’ method. From a resource utilization perspective, more coal can be extracted as less of it is retained in-situ in order prevent the mine roof from collapsing during the mining process. This has the double effect of both increasing yields as well as increasing miner safety, since miners are always under cover of the hydraulic roof support rather than relying on the remaining pillars of unknown integrity (Thomas 1973). From a public safety perspective, longwall mining also has the advantage in that the ensuing subsidence is generally predictable and occurs in conjunction with the mining process and not at some later, indeterminate date. This enables subsidence engineers to effectively plan for and manage many of the impacts of mining-induced subsidence (Singh 1992).

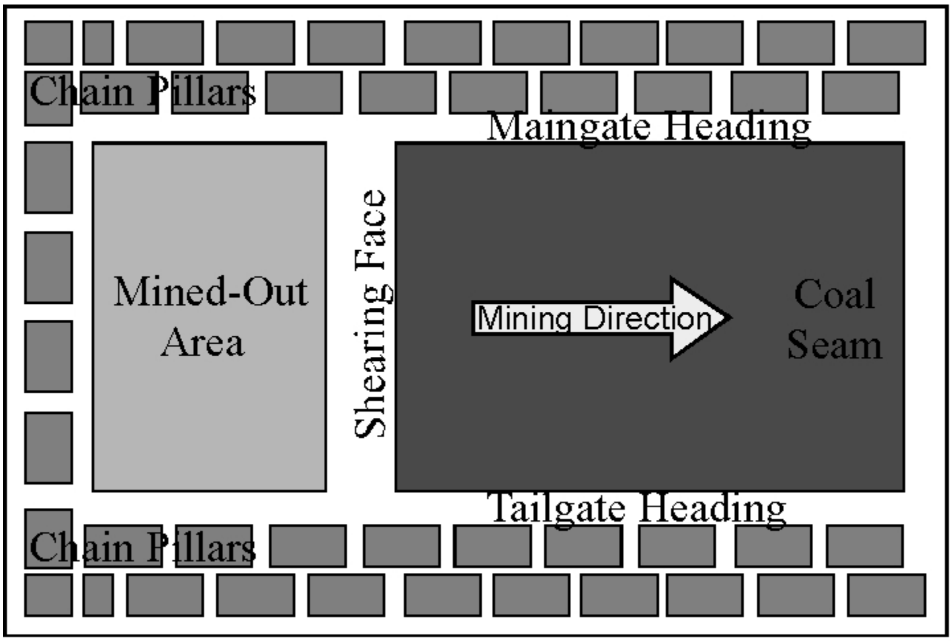


Figure 2.1. Longwall mining method, after Kratzsch (1983).

During the longwall mining process, coal seams are mined in long, rectangular strips, known as panels (Figure 2.1). Each panel is generally 250 – 300 metres wide, approximately 3 metres high and 2 – 3 kilometres in length, with chain pillars separating adjacent panels. These chain pillars are comprised of coal that is left behind and they function as roof supports, ventilation infrastructure, and underground roadways (maingate and tailgate headings) (Thomas 1973). To be profitable, each seam being mined will have multiple panels, and each mine site may mine multiple seams at varying depths. For a given mine layout, all panels are mined in the same direction, and multiple seams are generally mined in a spatially staggered manner so that the chain pillars are not simply stacked one on another, thereby minimizing the subsidence impacts at the surface.

Mining commences from an end ‘barrier pillar’ (Figure 2.2, A 1) (Kratzsch 1983). During the mining process the roof is only supported by hydraulic roof supports (Fig 2.2, A-3) in the vicinity of the active mining face (Fig 2.2, A-4). As the seam (Fig 2.2, A-5) is progressively mined the hydraulic roof support moves in conjunction with the extraction process (Fig 2.2, A-2). Once mining (and hydraulic roof support) has progressed a critical distance from the entry point (Fig 2.2, B), the roof strata (the overburden, Fig 2.2, A-6), fractures and collapses into the mining void. As this collapse cascades upward towards to surface it results in the formation of subsidence troughs (Fig 2.2, A-9), which are, in effect a change in surface topography (Fig 2.2, A-7).

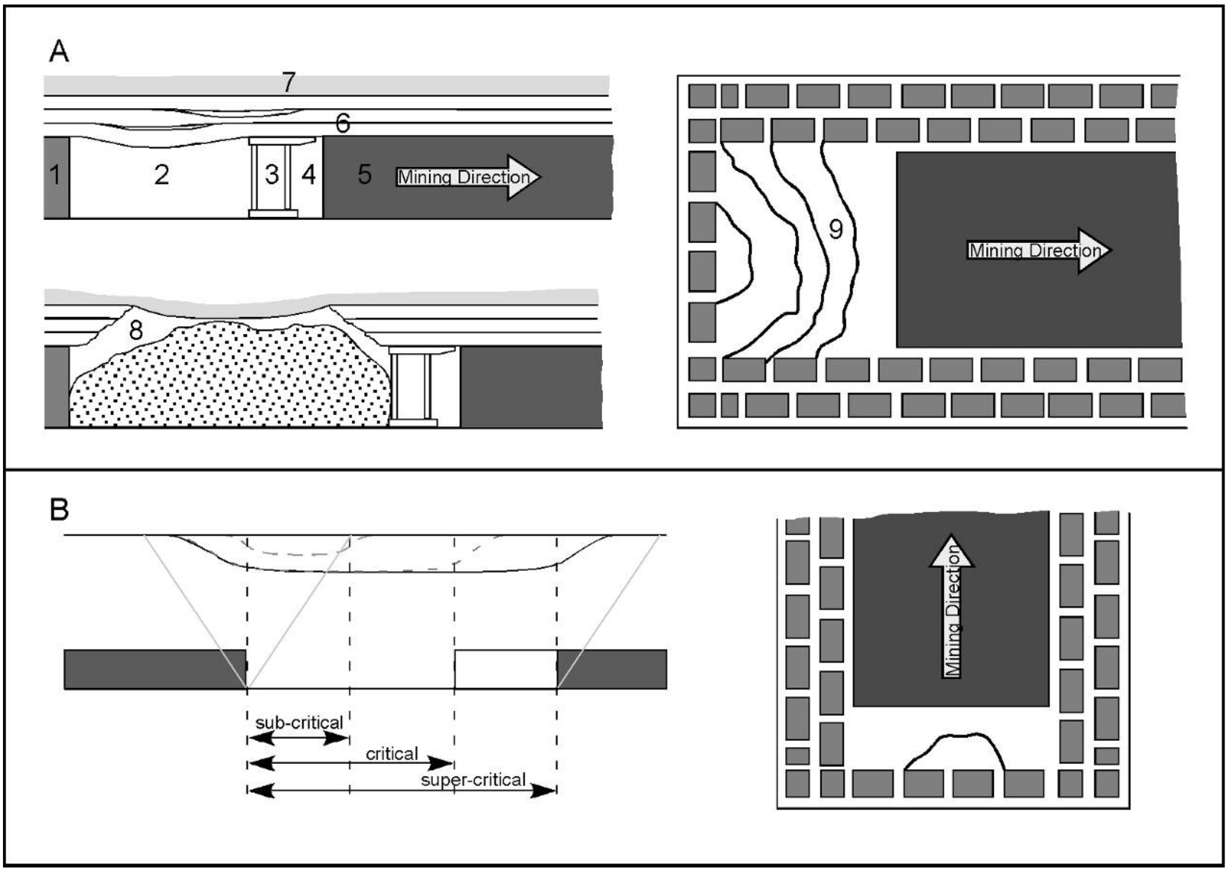


Figure 2.2. A. Longwall mining process and the creation of subsidence troughs. 1) The support pillar (chain pillar) mining entry point; 2) The void left by mined material; 3) The moveable roof support; 4) Coal face; 5) Coal seam in the mining direction; 6) Overlying strata, referred to as the overburden; 7) Surface topsoil; 8) Collapsed overburden, referred to as the goaf; 9) Formation of the subsidence trough. B) The creation of a subsidence trough, which is dependent on the width of the longwall panel. After Kratzsch (1983) and Thomas (1973).

Long wall mining-induced subsidence (LMS) encompasses all ground movements that occur due to the collapse of the overlying strata into mine voids created by longwall mining (Singh 1992). The magnitude and exact nature of ground movements depends on the mine layout, in particular, the length and width (Fig 2.2 B) of the longwall panel, the depth of the extracted seam, the thickness of the extraction seam, and the strength and nature of the overlying geological strata, as well as the topographic conditions at the surface (Bell *et al.* 2000; Kratzsch 1983; Thomas 1973). With longwall mining, the magnitude of subsidence generally amounts to 70 – 95% of the thickness of coal that is removed (Kratzsch 1983).

Whilst there are many important facets and components of LMS, the phenomena of angle of draw, tension and compression and active subsidence require further discussion as they have particular relevance to the work presented in this thesis.

2.2.1 Angle of draw

The creation of subsidence troughs on the surface is primarily a result of the vertical displacements of the overlying strata. Whilst these coincide with mining process and the removal of coal from the panel, it is important to realize that they extend beyond the area corresponding to that of the mined panel itself. This is due to the angle of influence or the angle of draw (Kratzsch 1983, 1986; Singh 1992), and is indicated by the light grey lines in Figure 2.2 B. The area beyond the mining panels that will be affected by subsidence can usually be calculated using an appropriate angle of draw and simple trigonometric relationships.

2.2.2 Tension and compression

Along with the horizontal displacements, subsidence also induces both a tensile and compressive strain at different points on the subsidence trough (Kratzsch 1983). These tensile and compressive forces are primarily a result of leaving coal behind for pillar supports. As the trough develops, areas over the pillars experience tensile stress as the ground is ‘pulled’ downward by the collapsing roof strata. These tensile stresses are primarily responsible for the creation of surface cracks developing as mining progresses (Bell *et al.* 2000; Kratzsch 1986; Palchik 2003, 2005; Singh 1992). Areas closer to the centre of the pillar undergo compression as the maximum subsidence is reached, with a concomitant compaction of the soils at the surface (Bell *et al.* 2000; Darmody 1998).

2.2.3 Active subsidence

Subsidence has two major phases, active or dynamic subsidence and residual, or long-term, subsidence (Goulty & Al-Rawahy 1996; Luo & Peng 2000). Active subsidence generally occurs in conjunction with the process of mining individual panels, and it generally accounts for the majority of the subsidence. Residual subsidence occurs after mining operations have ceased, and its overall magnitude is generally only a fraction of that of active subsidence (Goulty & Al-Rawahy 1996; Luo & Peng 2000). As active subsidence generally accounts for the majority of subsidence associated with longwall mining, this type of subsidence will be the focus of this thesis.

Once initiated by mining, subsidence is characterized by a ‘subsidence wave’ which travels along with the mining process and occurs when the hydraulic roof support moves forward (Goulty & Al-Rawahy 1996; Luo & Peng 2000). This process results in the creation of systematic and relatively uniform subsidence troughs on the surface that are clearly identifiable (Darmody *et al.* 1989; Darmody *et al.* 1988). As longwall mining has been conducted since the mid 17th century (US Department of Energy 1985) subsidence engineering has also become refined; indeed engineers are adept at predicting the magnitude and location of subsidence troughs (Figure 2.3 A & B) that are represented diagrammatically as subsidence isoclines or contours.

A B

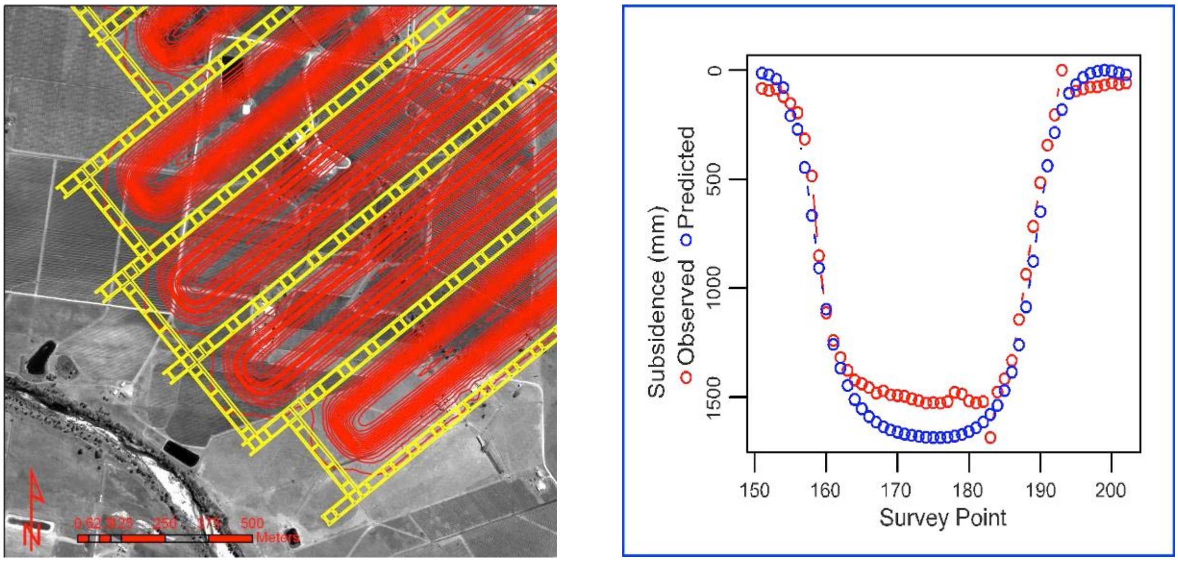


Figure 2.3. A) An example of predicted subsidence contours (red) over the study site used in this thesis (discussed in Chapter 3), with underground chain pillars highlighted in yellow. B) Actual vs. predicted subsidence over one of the longwall panels, measured at 10 m intervals. Data courtesy of Umwelt and Mine Subsidence Engineering Consultants.

2.3 Case studies - LMS and agriculture

Many of the physical surface-level impacts associated with LMS are reasonably well understood. For instance, topographic changes resulting from LMS are known to impact upon the built environment (Bell *et al.* 2005; Bell & Genske 2001; Bell *et al.* 2000; Bullock & Bell 1997; McNally 2000; Singh 1992). Similarly, LMS is known to affect both ground (Booth 1998, 2006; Booth & Bertsch 1999; Booth *et al.* 2000; Karaman *et al.* 1999; Karaman *et al.* 2001; Zipper *et al.* 1997) and surface water hydrology (Bell & Genske 2001; Bell *et al.* 2000; Sidle *et al.* 2000). Whilst environmental impacts associated with LMS on agricultural productivity have been reported in the literature (Darmody *et al.* 1989; Darmody *et al.* 1988; e.g. Donnelly *et al.* 2001; Guither 1986; Hinchliffe 2003; Hu & Gu 1995; Hu *et al.* 1997; Yunge &

Zhengfu 2004), there are relatively few systematic, quantitative case studies of the impact of LMS on agricultural productivity *per se* to draw upon.

Although it is commonly accepted that LMS can impact upon agricultural production, only the work of Darmody *et al*. (1989; 1988), Hinchliffe (2003) and to a lesser extent, Hu *et al.* (1997) provide reliable, quantitative data. To date, no examinations of LMS impacts upon vineyards have been reported in the literature. As such, the potential for viticultural impacts must be elucidated from the more generalized LMS agricultural impacts reported. The following section will describe the case studies of Bell *et al. (2000)*, Darmody *et al.* (1989; 1988), Hu *et al*. (1997) and Hinchliffe (2003) in detail.

2.3.1 Ruhr Region - Germany

As longwall mining originated in Europe (Thomas 1973), it makes sense to explore agricultural impacts attributable to it in the Ruhr Region of Germany, which has a long history of such mining. Underground mining in the region pre-dates the 18th century (Bell *et al.* 2000). Although it is unclear what proportion of this historical activity was associated with longwall mining, during the 1960s longwall mining in particular is known to have caused several problems in the area around Dortmund-Lanstrop in particular. As Bell *et al.* (2000) have chronicled these impacts, the following draws exclusively from their work.

Between 1963 and 1967, five coal seams in the area were mined using longwall techniques. Mining occurred between 300 to 500 m below the surface and the resulting subsidence created several issues. Roads were rerouted, sewer gradients repaired, and an old castle was shored up to prevent it from collapsing. In several instances, the troughs associated with LMS dipped below the water table, resulting in the formation of lakes and ponds.

The largest of these lakes, Lake Lanstrop measures some 200 metres across, 400 metres long, and is 9 metres deep (Figure 2.4). Prior to mining, the land upon which the lake now resides was used for agriculture, which is obviously no longer possible where the lake now exists. Subsequent to mining, the Lake has been stocked with fish, and has now become a nature preserve.

Figure 2.4. Creation of Lake Lanstrop (highlighted in blue) rendered underlying agricultural land unproductive. From Bell et al. (2001) and Google Earth (2008).

Though somewhat extreme, this example highlights one of the early documented examples of LMS impacts upon agriculture. In fact, this prompted Kratzsch (1986) to recommend farmers be compensated for yield losses where such subsidence results in ponding.

Aside from raising the issue of ‘ponding’ in relation to agriculture, this case study does not provide quantitative impact information. Although five seams were mined at depths of 300 – 500 metres within the area, Bell *et al.* (2000) do not indicate how many were mined, their relative locations nor do they provide any indication as to pre-mining elevation and slope, depth to aquifer, mining layout, mining direction, nor seam thickness, data which are considered essential in translating these effects to other locations and longwall mining operations (Singh 1992).

2.3.2 Illinois – United States

One of the first attempts to quantify subsidence impacts on agriculture can be found in the works of Darmody *et al.* (1989; 1988). Although the work of Guither (1986) had previously established that "depressions, standing water in depressed areas, surface drainage disruptions" resulting from LMS caused problems for corn (*Zea may*s L.) production, this work relied entirely on data collected from surveys of farm managers and hence it only provided qualitative estimates of subsidence impacts. To redress this situation, Darmody *et al.* (1989; 1988) developed a landscape scale methodology to acquire a quantitative understanding of LMS related impacts on corn (*Zea may*s L.), the predominant crop in Illinois. Furthermore, this early work then prompted Darmody (1995) to develop a GIS-based framework for assessing subsidence risk. However this later work did not represent an attempt to quantify impacts, but rather the GIS platform served a means of spatially referencing qualitative descriptors of change. Consequently, it is not further discussed here.

Using pre- and post-mining stereo-pairs of 1:12000 scale black-and-white infrared (BWI), aerial photographs, Darmody *et al.* (1988) surveyed 180 km^2 of the plains in southern Illinois. Slopes in the study area varied from zero to eighteen percent. The photos were acquired before yearly crop emergence during moist conditions. Mining areas were highlighted on the photos and viewing them stereoscopically allowed for the identification of subsided areas (Figure 2.5). From these images subsided areas prone to ponding were classified according the criteria in Table 2.1. The areas occupied by these classes were then calculated by superimposing a regular grid pattern and counting the total number of ‘dots’ these areas occupied. By limiting study areas to those with active mining operations any evidence of MS related impacts found when comparing the pre- and post-mining photos was attributed to mining activities.

A B

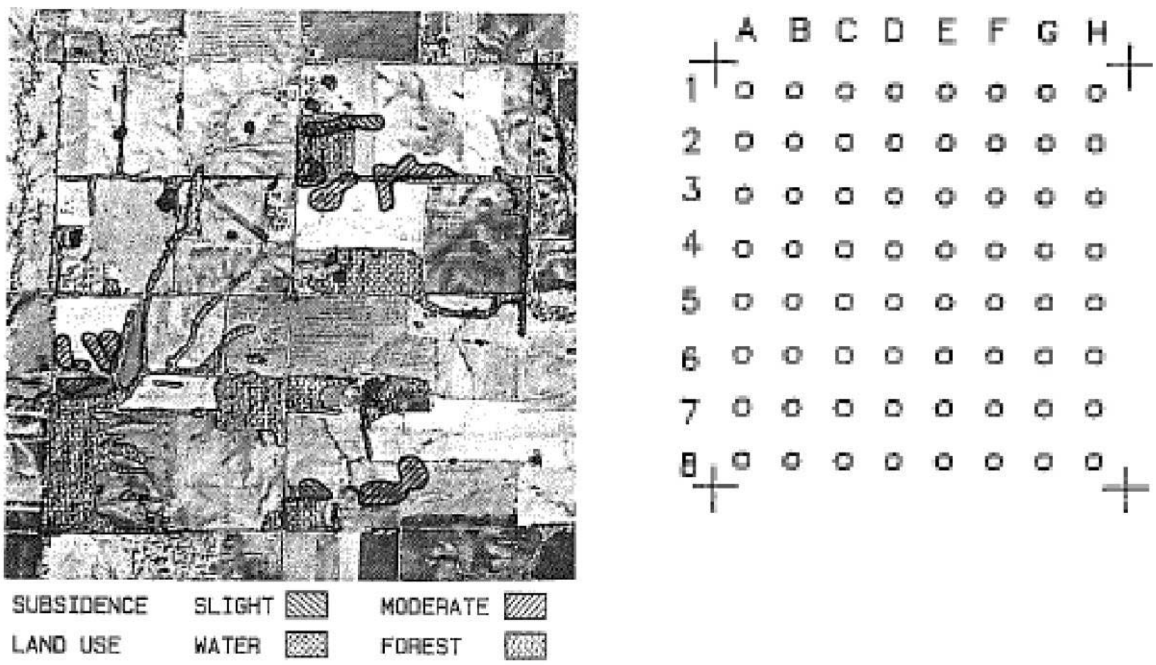


Figure 2.5. A) Example of Darmody *et al.*’s classified imagery. B) The sample grid used to determine the area occupied by each class. Each dot represents 4.05 hectares (40,500 m^2). From Darmody *et al.* (1988).

Table 2.1. Darmody *et al.*’s (1988) subsidence classes.

Subsidence Class	Evidence
None	No change from pre-mining photography
Slight	Topographic change without associated dark (low) infrared signatures
Moderate	Dark (low) infrared signature with topographic change
Severe	Ponding or black (i.e. lowest) infrared signature with topographic change

From the classified images, Darmody *et al.* (1989) identified specific areas for on-ground fieldwork. Areas covering the range of impacts (slight – severe) were then visited at harvest, and their yields were compared to a nearby field operated under the identical farm management practices. These non-impact fields served as a control site for the impacted sites. Hence, the percent reduction in yields could be calculated directly, according the formula:

$$Percent\ \ Yield\ Reduction = 100 * \left(\frac{Control\ Yield - Subsided\ Yield}{Control\ Yield} \right)$$

Across the three years of their study (1985-7), Darmody *et al.* (1989) found that longwall mining left more of an identifiable impact on the topography of the study area than did the other underground mining technique (high extraction retreat - HER) used in the study area. They also determined that the percentage of yield reduction varied by class, but was not affected by mining type. Table 2.2 presents their average impacted areas by mining type along with the average yield reduction measured across all years. They also found that moderate and severe impacts appeared to be influenced by slope and rainfall considerations; the majority of impacts sites were situated on relatively flat terrain and high levels of rainfall during the first year of the study meant more water was thus available for ponding. The distribution of subsidence-impacts by slope is presented in Table 2.3.

Table 2.2. Darmody *et al.*'s (1989) average percentage of subsidence-impacted areas by mining type combined with average yield reduction.

Subsidence Class	Average percent of mined area - LW (%)	Average percent of mined area – HER (%)	Average Yield Reduction - LW & HER (%)
None	64.7	91.2	-
Slight	27.8	5.5	-2
Moderate	5.2	2.9	-43
Severe	2.3	0.4	-95

Table 2.3. Darmody *et al.*'s (1989) distribution of moderate and severe subsidence impacts by slope range.

Slope Range (%)	0 – 1.5	1.5 – 4	4 – 7	7 - 12	> 12
Frequency (%)	53.6	27.6	13.0	5.8	0

The works of Darmody *et al.* (1989; 1988) are important in that they represent early attempts at systematically quantifying LMS impacts upon agriculture. In one sense, they appear to confirm what can only be loosely inferred from German examples from the 1960s (e.g. Bell et al.'s (2000) account) presentation of subsidence-induced agricultural impacts. In the more serious impact cases slope appears to be a significant factor as on flatter terrain it increases the potential for ponding. According to Darmody *et al.* (1989), in such cases subsidence related ponding effects are potentially exacerbated by both high rainfall events and the presence of shallow aquifers across the study region.

There are, however, some issues with their work that need to be addressed. The first problem relates to the survey methodology, particularly their lack of pre-impact assessment 'ground-truthing' and their use of the regular grid approach (Darmody *et* *al.* 1988). Although Darmody *et al.* (1988) conducted site inspections at harvest to determine the magnitude of agricultural impacts, they do not indicate whether or not the infrared aerial photography, was 'ground-truthed' to verify the link between identified zones of differentiation and potential drivers of crop yield. Indeed, no information was provided as to what the BWI imagery was discriminating; presumably indicating soil moisture, but shadowing or high soil organic matter could also have influenced it. Without such 'ground-truthing', it is difficult to estimate the overall accuracy of the method, as there is no way to assess what sites might have been included but should not have been (errors of commission) or which sites should have been included but were not (errors of omission) as other factors (e.g. shadowing, sedimentation) can partially confound such techniques.

Although expedient and efficient from a time-management perspective, the regular grid technique is also problematic in that it can skew results. Other than the fact that their grid scheme divides up their study areas conveniently, allowing for a rapid appraisal of 70 images, Darmody *et al.* (1988) provide no justification for the number and size of the sampling grid employed. In this sense, the units of measurement (4.05 ha) are essentially arbitrary and are not directly related to the objects of interest – subsided areas. As a result, simply changing either the size or number of cells in the gird will affect subsequent measurements and results. This is a typical example of the modifiable aerial unit problem (MAUP) as described by (Openshaw 1983).

The MAUP is a classic, intractable problem in modern geography. Quite simply, the problem arises through trying to study objects and their attributes, often people, indirectly using artificially constructed spatial units or zones, such as county boundaries, local government areas, census collector districts, wards, etc (Openshaw 1983). As the boundaries of these units are essentially arbitrary and are generally unrelated to the underlying properties of interest (e.g., socio-economic status, education, etc of people, households) a study's results can be changed simply by redefining the spatial boundaries, or modifying the shape of the aerial units. In general, "the principal criteria used in the definition of these units are the operational requirements of the census" (Openshaw 1983, p. 4), as was the case with the use of the regular grid approach adopted by Darmody *et al.* (1988). However, to verify their own methodology, on a series of test images Darmody *et al.* (1988) also studied the size of subsided areas using a digitising table. Comparing the percent difference in the results obtained using the digitised data with that of the grided data demonstrates the problem (Table 2.4); for all impact classes (slight – severe) the regular grid overestimates the areas assigned to each class.

Table 2.4. Comparison of the results obtained by Darmody *et al.* (1988).*

	Method			
Subsidence Class	Area by Grid (%)	Area by Digitizer (%)	Percent Difference (%)	Number of subsidence instances - Grid
None	94.6	95.8	- 1	4238
Slight	3.6	3.0	+ 20	161
Moderate	1.6	1.1	+ 45	72
Severe	0.2	0.1	+ 100	9

* First two columns are from Darmody *et al.* (1988), whilst the second two are based upon my own calculations.

Although Darmody *et al.* (1988) determined these differences were not statistically significant, that result is more likely to have been a function of the relatively few incidences of impact classes (slight – severe). The total number of observed instances of all subsidence classes obtained from 70 images is presented in the final column of Table 2.4. To compare the techniques, Darmody *et al.* (1988) randomly selected 20 images and, although there is no way to determine what proportion of the total instances were found on these 20 images, it is likely to have encapsulated significantly less than half of them. However, the difference in results obtained by the two methods highlights the need to study subsided areas directly, wherever possible.

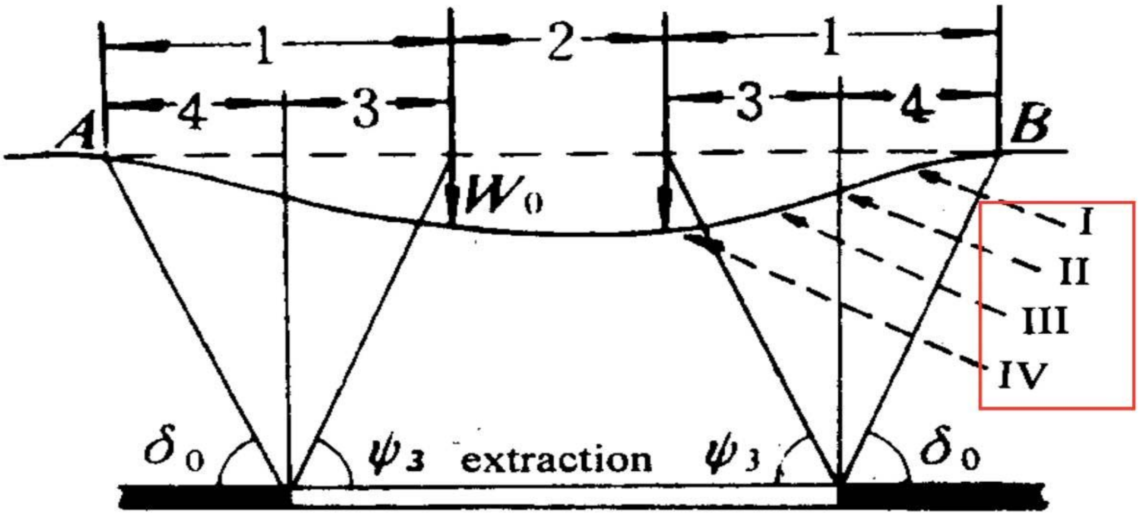
Another limitation of the work of Darmody *et al.* (1989; 1988) is related to the aims of the study. Darmody et al. (1989; 1988) were surveying the landscape for subsidence-induced impact upon agriculture, but the impacts they were trying to identify were those identified and highlighted by Guither (1986). That is to say, it was not Darmody *et al.'s* (1989; 1988) intent to study exactly when, how or the circumstance surrounding LMS impacts on agriculture but rather to essentially confirm Guither's (1986) results with a more objective methodology.

As such, it does not provide any indication of other potential impacts; it merely highlights one type of agricultural impact, that of ponding. For instance, the longwall mining process is known to release substantial quantities of methane (Diamond *et al.* 1997; Palchik 2003), which can adversely affect plant growth on the surface if it escapes through surface cracks. Certainly the work of Darmody *et al.* (1989; 1988) is important in that it quantitatively highlighted the important role that terrain (e.g. slope) and rainfall play in the formation of subsidence-induced ponding and its subsequent impacts upon agriculture but its limitations must be recognized.

2.3.3 Anhui Province - Eastern China

In recent decades, substantial quantities of coal have been extracted via longwall techniques in China. Much of this mining activity has occurred in the Anhui Province, a region also known for its agricultural productivity (Hu & Gu 1995; Hu *et al.* 1997; Zhengfu 2001). As such, there have been several studies pertaining to LMS and agriculture (e.g. Hu & Gu 1995; Hu *et al.* 1997; Zhengfu 2001). Although most of the work reported in the literature pertained to the reclamation or rehabilitation of impacted agricultural lands (Hu & Gu 1995; Zhengfu 2001), Hu *et al.* (1997) examined the potential impacts LMS had upon agricultural land.

Hu *et al.* (1997) selected three study sites. One site had been recently (preceding two years) subsided, one was subsided ten years previously, and one un-subsided plot was selected for comparison. At both impacted sites they noticed that the creation of subsidence troughs had two visible effects on agricultural lands, including the formations of surface cracks and the accumulation of water (ponding) at the bottom of the troughs. Hu *et al.* (1997) also noticed that there were obvious zones, with similar characteristics associated with subsidence troughs (Figure 2.6). They divided the trough into four zones, the centre zone of maximum subsidence (IV), the top trough zone corresponding to the areas of maximum tension (I), the bottom trough zone corresponding to the areas of maximum compression (III), and the middle point between them (II) (Hu *et al.* 1997).



1 -- subsidence prone land, 2 -- centre of subsidence trough, 3 -- inner-edge zone, 4 -- trough margin, I ~ IV -- soil sampling positions, I, II, III -- top, middle, bottom of the prone land respectively, IV -- centre of the trough.

Figure 2.6. Subsidence zones identified by Hu *et al.* (1997). The red square highlights the zones, which correspond with: I – Top, II – Middle, III – Bottom and IV – Centre. Source Hu *et al.* (1997)

At both sites, Hu *et al.* (1997) examined the impact of LMS on agricultural soil properties associated with these four zones. In particular, they were concerned with: the soil physical properties of bulk density and moisture content; the chemical properties of organic matter, nitrogen and phosphorus content, pH and electrical conductivity; and the biological property of plant biomass (Hu *et al.* 1997).

At both subsided plots, Hu *et al.* (1997) determined several of the properties appeared to follow a gradient that corresponded to that of the subsidence trough. Thus, increases in soil moisture, bulk density, and electrical conductivity corresponded with the progression from the relatively unsubsided top of the trough through the maximally subsided centre of the trough. They observed similar trends with organic matter and pH, although the area of the centre (Zone IV in Figure 2.6) had lower organic matter and pH than its closest neighbouring zone, the area of maximum compression (Zone III). Biomass followed an opposite trend; biomass at the top of the trough was highest and it steadily decreased in accordance with progression down the trough.

The work of Hu *et al.* (1997) is important in that it not only highlights the potential for altered drainage regimes to impact upon agricultural production, it also draws attention to other, previously unreported impacts. Like Germany's Ruhr Region, it is the changes to drainage regimes and the presence of shallow aquifers that is responsible for many of the impacts observed by Hu *et al.* (1997). The changes to soil moisture, biomass, electrical conductivity and pH are presumably a result of changing the way in which water moves and then accumulates across this landscape.

One of the additional impacts highlighted by Hu *et al.* (1997) was the increased risk of soil erosion that accompanied the changes in slope and the creation of subsidence troughs. Although the recently subsided and ten-year subsided plots only experienced 2 m and 3m (respectively) of subsidence this was sufficient to result in an increase in soil erosion. They theorized that it was erosion events that were mostly responsible for the observed differences in soil organic matter throughout the subsidence zones.

One of the problems with work of Hu *et al.* (1997) is their inadequate reporting of their study design and methodology. Whilst it is clear they have compared two subsided plots with an un-subsided plot, further details were not provided. Although Hu *et al.* (1997) note that observations were made at various positions corresponding to the zones presented above, they give no indication as to how many, nor the arrangement of measurements. Their replication strategy, if it existed, is not presented.

In addition, Hu *et al.* (1997) failed to provide sufficient detail on the criteria used to define the boundaries of the various zones. As noted in the previous discussion of the work of Darmody *et al.* (1988), the definition of zones can have a significant impact upon analytical results. Although it is clear that Hu *et al.* (1997) defined their zones to correspond with particular subsidence attributes (and hence are not completely arbitrary), these criteria should nonetheless have been stated explicitly.

2.3.4 Emerald – Australia

Like Darmody *et al.* (1989; 1988), Hinchliffe (2003) sought to quantify the impact LMS had upon agricultural production in Queensland's Bowen Basin near the town of Emerald. Hinchliffe conducted experiments which attempted to measure potential impacts on annual cropping systems, particularly wheat and soy bean production.

To do so, Hinchliffe conducted a series of cropping experiments on two different study sites. These study sites had been previously subsided; one site two years before and the other seven years before the experiment began. Like Hu *et al.* (1997), Hinchliffe (2003) was concerned with the nature of troughs in the subsidence zone and their potentially different impacts upon productivity. Hence, at each site he measured seed protein and moisture, germination, and yield across four different zones. Each zone consisted on ten 10 m x 10 m replicates, and zones were comprised of minimally subsided areas above chain pillars, maximally subsided areas above the centre of longwall panels, the transition area between them, and an un-subsided area for comparison (Figure 2.7).

Figure 2.7. A representation of Hinchliffe's site layout, based on Hinchliffe (2003). Yellow 'hatched' regions represent mining subsidence and the 'blocked' regions represent chain pillars.

From each replicate, a series of soil measurements was also obtained. These included extracting soil cores, measuring bulk density, measuring compaction with a cone penetrometer along with an analysis of water content and potential. Soils from the cores were characterized, which included an examination of particle size distribution, chemical analysis and their ability to retain water.

Over the two years of the study, Hinchliffe (2003) did not find any clear evidence to suggest that LMS negatively impacted agricultural productivity on either site. This is not surprising considering that no baseline details of soil type and variability across the sampling area were provided. Depending on soil type an increase in bulk density or tendency to pond may actually improve productivity in a situation of a season characterised by, for example below-average, light-showery rainfall. Although there was some evidence that LMS had positively affected yields on the more recently subsided site, such effects were not consistently observed at both sites. As a result, Hinchliffe (2003) concluded that, where evident, LMS effects were likely to be highly site specific and localized.

The work of Hinchliffe (2003) is important as it represents only the second reported attempt to quantify the potential impacts of LMS on agricultural productivity. While Hu *et al.* (1997) were also concerned with the impact LMS had on agriculture, it is important to note that at the time of their study, neither of their subsided study sites could be used for agriculture, due to the accumulation of water. As such, Hu *et al.* (1997) had to resort to a comparison of soil properties, and not agricultural productivity, between subsided and un-subsided areas.

Whilst Darmody *et al.* (1989; 1988) also sought to quantify subsidence impacts on agricultural productivity, there is one important difference between their work and that of Hinchliffe (2003). Unlike Darmody *et al.* (1989; 1988) who were attempting to quantify impacts at a landscape scale, Hinchliffe (2003) was essentially concerned with potential impacts and differences arising from the systematic nature of longwall mining. This is evident in the representation of the site layout presented in Figure 2.7; the arrangement of replicates along subsidence contours (replicates aligned by subsidence zones) suggest that he was concerned with the systematic nature of subsidence trough and wanted to know if their creation would also affect agriculture in such a systematic manner.

There is, however, one potential issue with the work of Hinchliffe (2003). Where longwall mining occurs in conjunction with agricultural activities, it is not uncommon for the land above mines to be rehabilitated and re-contoured, in order to prevent ponding and its associated impacts (Darmody 1998; Darmody *et al.* 1989). Unfortunately, because Hinchliffe (2003) does not provide any indication as to the overall magnitude of subsidence present in the various zones of his study sites, it is not clear whether or not they were subjected to remediation measures at any stage.

2.3.5 Case study summary

From these limited available case studies, it is possible to assemble a profile of known LMS impacts on agriculture. Because the impacts reported in the literature are not always consistent or identical, Hinchliffe's (2003) conclusion that, where evident, LMS effects were likely to be both highly site specific and highly localized is most likely correct, if not obviously so. This further suggests that every instance of undermining of agricultural crops requires detailed monitoring for potential impacts rather than *a- priori* modelling or estimation.

In many of the case studies presented, water accumulation or ponding was found to be a significant contributor to agricultural impacts (Bell *et al.* 2000; Darmody *et al.* 1989; Darmody *et al.* 1988; Hu *et al.* 1997). Hence, impacts are more likely where topographic changes result in significantly altered drainage patterns. This will not only depend on the overall magnitude of subsidence, but will also depend on soil type and characteristics, and overall topography. In flatter terrain, where aquifers are present close to the surface and where subsidence troughs cause the water table to 'rise' it is more likely that water will persist throughout the year. On soils that don't drain particularly well, water accumulates as a result of rain events, even if there are no aquifers close to the surface. In this later case, ponding may be seasonal and coincide with the rainy season.

Other potential impacts include damage resulting from the tensile and compressive forces generated at the margins of the mined panel. The compaction associated with the compressive forces could impede plant growth and development. Cracking associated with the tensile stressors may cause root sheer, as well as affecting soil moisture as water is lost down them. Because imperfections in the underlying strata are the predominant driver of crack development, their appearance is basically unpredictable as the strata imperfections are not readily apparent on the surface (Palchik 2003). They are, however, more likely to appear at the interface between chain pillars and longwall panels (Carpenter 1997).

2.4 Wine Grape Phenology

In order to fully understand and appreciate the study area and design of this present work, it is first necessary to have a basic understanding of the phenological cycles of grape vines (*Vitis vinifera*). There are a number of factors that influence a vine's progression through its annual cycles, and these include the 1) variety, 2) region, 3) season and 4) viticultural practices (McIntyre *et al.* 1982).

Unlike the crops studies in the previously reported case studies, the grape vine is a perennial plant subject to a recurring annual growth and development cycle. As expected, the annual cycle of a grape vine has two major components, a vegetative and reproductive cycle. Both components generally follow seasonal cycles as is evident in Figure 3.5A, though they are also influenced by local, seasonal variation (Figure 3.5B). For vineyards within the study area, the annual cycles are generally offset (earlier) due primarily to climatic conditions. Hence, harvest occurs earlier in the year by some 6-8 weeks and this is depicted in Figure 3.5B. It is important to note that vines can temporarily tolerate water-logged soils when fully dormant, but once new root growth has commenced water-logging can be detrimental to vine health (Gladstones 2004). In terms of being able to withstand ponding resulting from LMS, this growth period roughly corresponds to mid- to late-May through to early- to mid-August for the region containing the study area.

Outside of this time frame, ponding can affect vines differently, depending on when it occurs. Early in the season, it is most likely to inhibit growth. Excessively wet, cold and cloudy weather around flowering is likely to either cause one of two conditions: berries either start to fall off when too small (poor set or *coulure*) or incomplete, unproductive berries start to form (*millerandage*) (Gladstones 2004). Hence, flowering is a critical time for berry development and thereby impacting overall yield at the end of the season.

However, later in the season, climate and water are also important factors for overall vine yield. When berries start to ripen excess water increases the risk of vines becoming infected by diseases such as downy mildew or botrytis (Gladstones 2004). Again, too much water during this time can also negatively affect overall yield.

A B

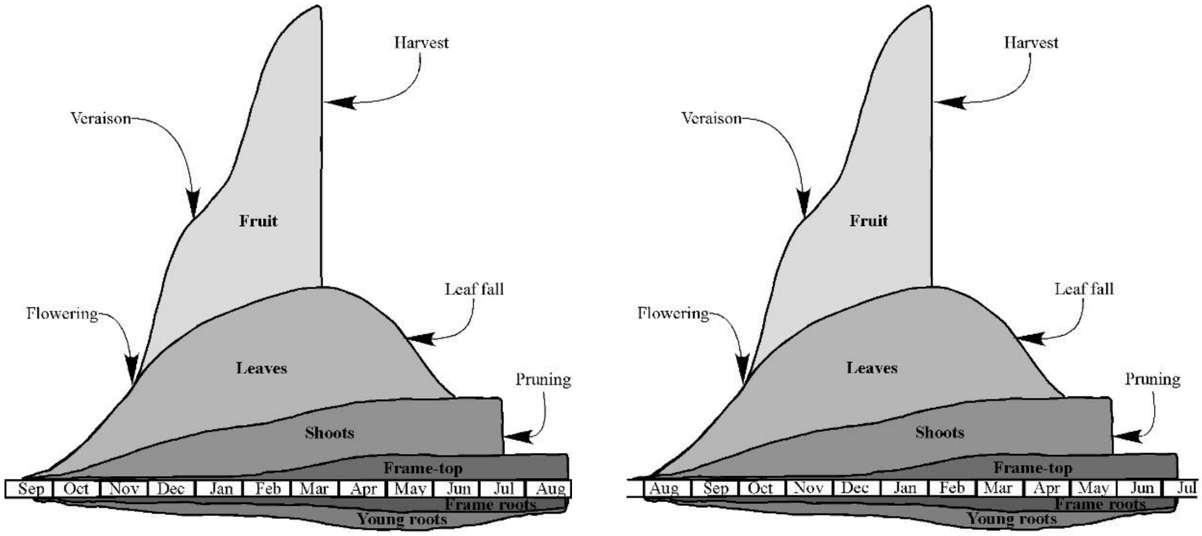


Figure 2.8. A) Generalized annual growth patterns of grapevines in Australia. B) Annual growth patterns adapted for the Broke-Fordwich Region.
A) Source: Pearce and Coombe (2004); B) Adapted from Pearce and Coombe (2004)

Although too much water at the wrong time can adversely impact upon both plant health and berry development, water is also the significant driver of overall yield. Quite simply, whilst too much water causes issues with overall plant health, too little water can inhibit or reduce yields significantly. Once berries have set, over the next ~120 days they take on significant quantities of water during their formation and ripening phase (Coombe & Iland 2004; Gladstones 2004). Much of the overall mass berries eventually achieve is acquired during days 30 to 90, as is evident in Figure 2.9. Late in the season, particularly in the last 30 days prior to harvest, heat stress and associated water loss also pose a significant risk to overall yield (Gladstones 2004).

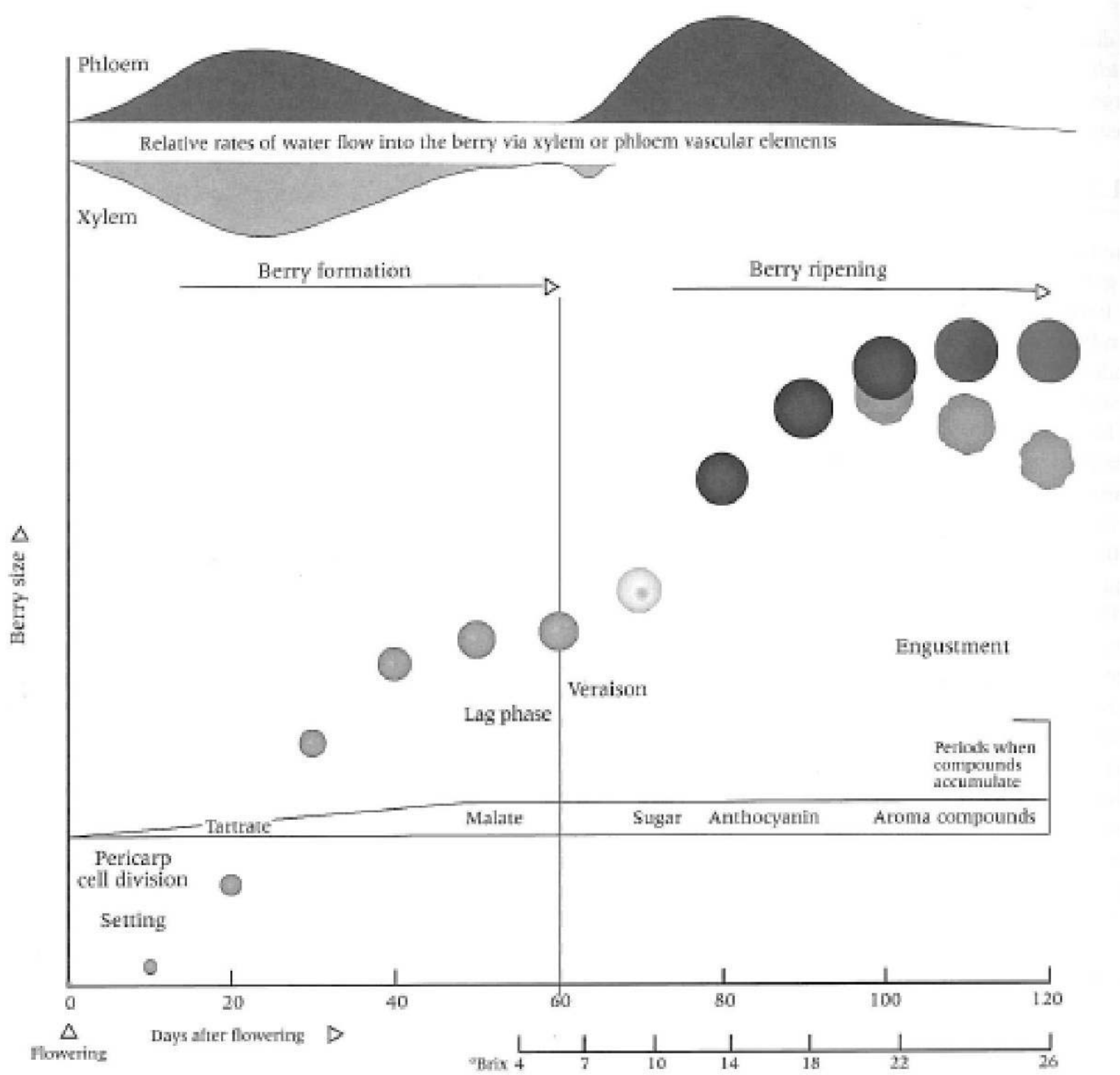


Figure 2.9. **Post flowering, the berry development and ripening (Veraison) cycle is completed roughly 120 days later. From Coombe and Iland (2004)**

2.5 Environmental Monitoring

2.5.1 Detecting Environmental Impacts

Trends are common in environmental data and not all trends are a result of human intervention. Data may exhibit trends that may be associated with a 'steady state,' or they may reflect changes to that state induced by natural climatic events (Smith 2002). Differentiating between 'natural' and 'man-made' causes in order to attribute causality to human intervention is difficult and often requires a combination of statistical modelling and professional expertise (Conquest 2000).

One of the methods for assessing environmental impacts is the Before-After (BA) methodology (Green 1979). In this method, observations on the state of a site are collected before an impact or intervention occurs. These 'before' observations are then compared with observations collected after the impact has occurred, and differences between the two are attributed to the impact or intervention. A variation of this method (BA_V) can be used when few or no 'before' observations are available from the impacted site (e.g. in the event of an oil spill) and observations from a nearby, un-impacted site are then substituted (Smith 2002).

One of the difficulties with this methodology is again separating 'natural' from human induced changes that occur through time. However, such temporal trends are not an issue with the variant (BA_V), as they are generally not studied at vastly different times. However, natural variations due to their different spatial locations are inevitable. Hence, in these scenarios it is then difficult to differentiate between differences that are a result of spatial location and those that occur as a result of human impact. Due to the fact that neither collected data on the impact site prior to mining, but rather compared impacted sites to un-impacted sites after the fact, both Hu *et al.* (1997) and Hinchilffe (2003) can be considered as belonging the BA_V method.

An important derivative of the BA design is the Before-After, Control-Impact (BACI) method. This method attempts to account for both spatial and temporal variability by making observations at the impact site at times before and after impact and comparing them to before and after impact observations of an un-impacted site

(Stewart-Oaten *et al.* 1986). With this method, the magnitude of the differences (solid vertical lines in Figure 2.10) between the control and impact sites are compared with the magnitude the differences between them after the impact (dashed vertical lines in Figure 2.10). Significance differences are assessed using statistical methods (either two-sample *t*-test or ANOVA interaction test) (Smith 2002). Because this method uses a comparison between the impact and control site, it is sometimes referred to as the BACI paired (BACIP) model (Smith 2002). Although other, hybrid BACI-type models are possible, they represent variations on these basic models.

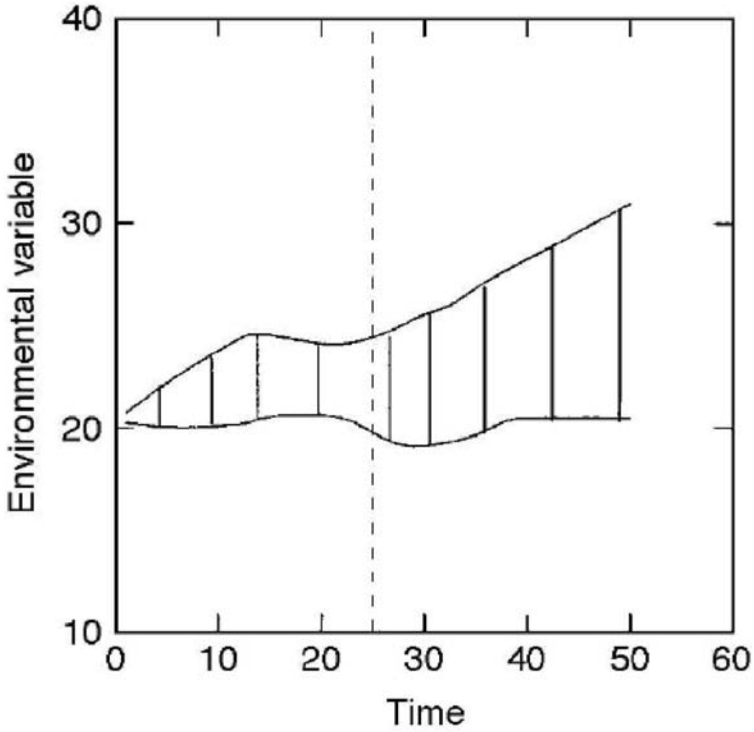


Figure 2.10. Example of a BACI comparison. The magnitude of the differences between the control (upper line) and impact block are statistically analysed for difference before and after impacts, as indicated by the vertical dashed line. From Smith (2002)

2.5.2 Vineyards and Monitoring Complications

From a monitoring standpoint, viticultural regions present certain operational and analytical difficulties. Across a region, vineyards tend to be designed, owned and managed individually. Individual vineyards are rarely homogenous in that most vineyards contain blocks with different grape varieties, sometimes with different trellising systems and management requirements. Within a vineyard, vines are generally managed on a per block basis, with all vines within the block being subjected to some common management practices, such as watering, fertilising and pesticide applications. However, in order to produce a consistent product, blocks are actively managed on a per-vine basis to reduce variability in product quality, such as pH, titrateable acidity (TA) and total soluble solids (°Brix). This management may take the form of pruning, shoot thinning or (pre-harvest) bunch removal to name but a few. Thus, individual vines within a given block are often managed differently, both during the growing and dormancy (pruning) 'seasons'.

In areas where longwall coal mining and viticultural activities occur together, subsidence impact monitoring programs that include viticultural impacts must be capable of dealing with all of these complexities. By necessity, developing an appropriate monitoring protocol for viticultural regions requires an interdisciplinary approach. Whilst standard viticultural assessment methodologies, such as 'panel sampling', are able to monitor a block's quantitative and qualitative productivity, their intensive, on-ground sampling requirements preclude application across an entire viticultural region.

2.5.3 The role of Global Positioning Systems (GPS) and Precision Agriculture (PA) in above-ground LMS monitoring

The emergence of low cost, highly accurate (sub-metre resolution) global positioning systems has lead to the rise of 'precision agriculture'. Precision agriculture has been defined as "a management strategy that uses information technologies to bring data from multiple sources to bear on decision associated with crop production" (National Research Council 1997, p. 2). One of the major differences between conventional and precision agriculture has involved using these technologies to "provide, process, and analyse multiple data of high spatial and temporal resolution for decision making and operations in the management of crop production" (National Research Council 1997, p. 2). In general, it has three main components:

1. *The capture of data at an appropriate scale and frequency;*
2. *The interpretation and analysis of that data; and*
3. *The development of an appropriate management response at an appropriate scale and time.*

(National Research Council 1997, p. 2)

Precision viticulture is a sub-branch of this broader field of precision agriculture. As such, it relies upon the application of spatial-based technologies to monitor vine productivity (canopy development, grape yield and grape quality) and it further incorporates geophysical sensing of soils and mapping of related vineyard attributes (e.g. topography) for vineyard management purposes (Proffitt et al. 2006).

Remote sensing technologies are ideal for collecting data from larger areas over a relatively short time frame. Aerial and satellite imaging systems, for instance, can sample an entire region instantaneously, whilst ground based, on-the-go sensor platforms can sample entire vineyards within a few hours.

Such remote sensing technologies have been used successfully in viticultural applications previously. For instance, Bramley and Hamilton (2005; 2004) have used a combination of on-the-go yield monitoring data acquired using a mechanical harvester and differential global positioning system (dGPS) to map spatial variability of vine yield (t/ha) within a vineyard.

On-the-go, dGPS-based geophysical, soil prospecting methods, in particular electromagnetic (EM) induction soil surveying, are now widely-used to map spatial variability in soils (Proffitt et al. 2006). Whilst EM38 measurements are not directly linked to vine health they are a measure of soil physical properties, in particular soil moisture and soil ion content (Corwin & Lesch 2005). In a mining context, Carpenter (1997) utilized the connection between measured EC_a and soil physical properties map LMS soil fractures over active longwall panels. Furthermore, Johnson *et al*. (2001) have suggested EC_a is well suited for the longitudinal monitoring of soil physical properties.

The use of remotely sensed, multispectral imagery has proved useful for mapping incidences of disease in vineyards (Baldy et al. 1996; Johnson et al. 1996; Johnson et al. 2003), canopy biomass at pruning (Dobrowski et al. 2003) and grape quality (Lamb et al., 2004) and yield (Hall et al. 2008). The work of Hall *et al.* (2003) is particularly relevant, in that it demonstrated that multispectral imagery could be used to map the relative vigour of grape vines. In particular, they established a link between a vine's observed reflectance and its photosynthetically active biomass (PAB). Furthermore, Hall *et al.* (2003) suggested that this relationship was still valid even up to the point where the image's spatial resolution (as determined by the on-ground dimensions of image pixels) approached the spacing of vine rows.

The outstanding limitation in all of the earlier cited work dealing with LMS effects on agriculture is the failure to adequately accommodate the 'natural' spatial variability in the landscape associated with the system in question. The fact that PA tools aim to account for significant spatial variability in soils and the complex, concomitant interactions with plants that affect production (yield and quality) at both the intra- and inter-paddock scale, provides an obvious opportunity to revisit the issue of LMS on agricultural lands. Candidate technologies include using GPS-equipped electromagnetic induction soil surveying, GPS-equipped yield and quality monitors on harvesters and new indices describing crop plant biophysical condition based on air- and satellite-borne remote sensing. Certainly there are no cases in the literature purporting to have examined the impacts of LMS on viticultural production using the tools of PA. Notwithstanding the limitations of the previous work, the case studies do assist in the formulation of a series of null hypothesis regarding the potential impacts of LMS on viticultural productivity. These null hypotheses can be expressed as follows:

- Longwall mining induced subsidence affects viticultural production in a localized, site specific manner; and

- Longwall mining induced subsidence has no significant (e.g. not moderate/severe) effect on viticultural production (vine yield).

In particular, the first hypothesis attempts to establish whether or not the systematic nature and formation of subsidence troughs has a similar, systematic effect on viticulture. That is, is there evidence that potential impacts and collected data have particular characteristics consistent with a relevant subsidence zone? It is reasonable to expect that the finite spatial extent of longwall mining would impart some form of spatial limitation on the above ground LMS effects in terms of viticultural production, as subsidence and ensuing ground 'strain' are not uniformly distributed across undermined areas. Since grape vines are deep rooting plants, it is reasonable to expect some form of differences in the growing environment before and after mining, with the transition between the lesser-affected areas above the chain-pillars and the areas of maximum subsidence of the longwall potentially being the most heavily impacted (following the consideration of Hu *et al*. (1997)). This is due to the fact that this region encompasses both the maximum and minimum induced strain, which could impact the roots either by compacting or sheering them.

The second hypothesis was formulated with particular reference to Darmody *et at.* (1989; 1988), where more serious impact categories were derived on the basis of the presence or absence of accumulated water (ponding). Hence, this hypothesis attempts to determine whether or not there is any evidence of differential changes in apparent electrical conductivity (EC_a) that would be indicative of water starting to accumulate (sub-surface) in subsidence troughs in the vineyards. That is, is there evidence of ponding post-mining and has that ponding negatively impacted upon vine yield?