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**C. A. Llewellyn**

**Practical soil protection and stabilization in Mediterranean  
viticulture**

**Supervisor: Dr R. J. Rickson**

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## ***Abstract***

The accelerated erosion of soil by water from Mediterranean hill-slopes under viticulture is a major problem. It is largely a result of the land management techniques employed and their influence on soil protection, structure and stability.

Within this study, the relationships between viticulture practices, soil physical characteristics and erosion processes have been explored in detail, and a soil conservation strategy, which incorporates the use of herbicide managed cover, has been developed.

The strategy was applied and tested in two established vineyards in southern France over a three year period (October 2001 to December 2004). Sediment and runoff losses were monitored at the plot scale from the date of treatment installation and comparisons were made with the losses from plots under conventional soil management.

Cultivation, to produce a fine seedbed for cover establishment, encouraged soil to become hydrophobic and impeded drainage at depth. This aggravated soil losses under saturated conditions and impeded cover establishment. However, total sediment losses were reduced by the presence of a cover at both sites within the monitoring period. The results of a 'Visual Soil Assessment' showed that there was a measurable improvement in the physical condition of the soil of the vegetated plot three and a half years after the cover was sown.

Controlled laboratory studies were conducted to identify the most suitable herbicide product and dose rate for inducing dormancy in a grass cover, whilst retaining its protective and stabilizing properties. Two products were tested: Paraquat and Glyphosate. At 21 days after treatment application, the treatment effects on plant and soil physical characteristics were assessed. Herbicide product and dose were found to indirectly influence a soil's potential to erode but more detailed studies are required. Initial results suggest that Paraquat is the more suitable of the two products tested.

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The study concluded that herbicide managed permanent cover is a practical option for soil conservation in Mediterranean viticulture.

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## **1. Introduction**

Throughout the cultivated lands of the Mediterranean the accelerated erosion of soil by water has become a major problem. A large proportion of this soil loss is directly associated with the production of grapes, olives and top fruit, (Garcia-Torres & Martinez-Vilela, 2002; Martinez-Casanovas & Sanchez-Bosch, 2000; de Graaff & Eppink, 1999 and Tropeano, 1983).

Over the years, traditional cultivation methods for these crops have been abandoned in favour of mechanical assistance, and economic incentives have encouraged greater production and the use of marginal land (EUROPA, 2003, Beaufoy, 2001; de Graaff & Eppink, 1999). Plantations are commonly set out in rows, often aligned up-slope down-slope, and soil is kept bare to avoid the perceived threat of water stress and frost damage to buds caused by ground cover. The exposed soil is left at the mercy of rain splash and runoff forces in a climate which is renowned for its intensive storms. As a result, the soil is often eroded so extensively that the crops are destroyed and the land is rendered unfit for agricultural production, roads become impassable, ditches become blocked and water supplies are degraded.

Vines, olives and top fruit are crops on which many countries' economies have been built and on which they have come to depend (Beaufoy, 2001; de Graaff & Eppink, 1999; Mullins *et al*, 1992 and Winkler *et al*, 1974). Thus, changes to production methods are necessary if economic and environmental disaster are to be avoided.

In October 2001, a soil protection communication was produced by the European Commission. This communication was the first step towards the establishment of a European soil protection strategy which, if implemented, would require farmers to adopt management practices which favour soil conservation.

There are a number of engineering techniques which can be practiced to reduce soil erosion but the majority are expensive to implement and maintain and would require significant changes to plantation layout. It is therefore anticipated that more

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economical methods, which have minimum impact on plantation design and the primary crop, will be in great demand.

Vegetative cover has long been accepted as one of the most effective means of conserving soil and improving soil condition (Lal, 1994). However, for successful integration with an established cropping system, the type of cover and management require careful consideration.

It is believed that in many perennial cropping systems the use of permanent grass cover would become more widely accepted if, during critical periods in crop growth, a state of artificial dormancy could be achieved. Managing the cover in this way would:

- reduce competition for water and minerals,
- provide year – round erosion protection for the soil,
- provide a continuous supply of organic matter,
- improve soil structure, and
- enable natural regeneration of the cover when conditions become appropriate.

It would also avoid the need for cultivation and re-seeding each autumn; often carried out under cover cropping, which not only damages soil structure but leaves it vulnerable to rain splash and runoff.

In 2001, a research programme was launched by Syngenta to develop a soil conservation strategy which included the use of Paraquat (a non-systemic contact herbicide) as a cover management tool. This product is used globally in a wide variety of cropping systems as a means of total weed control. It kills annual weeds but woody crops and the roots of perennial plants remain unaffected (Brown *et al*, 2004).

The research was directed primarily at soil protection in the perennial cropping systems of the Mediterranean. The objective was to provide farmers with an economic and environmentally acceptable alternative to existing soil management practices.

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This study plays a key part in that research programme and it aims:

- **to contribute to the development of a soil conservation strategy, suitable for use in Mediterranean viticulture, and**
- **to demonstrate that strategy's effectiveness at conserving soil.**

Several steps have been taken to achieve these aims, the first and most important of which is a comprehensive evaluation of:

- the requirements of the vine, current cultivation techniques and their influence on where vines are grown and how the soil is managed,
- the cause and the scale of the soil erosion problem in Mediterranean vineyards, and
- existing soil conservation methods and their compatibility with Mediterranean viticulture practices.

Understanding of these topics is fundamental to this research. Without an appropriate degree of understanding, sensible solutions to the problems cannot be proposed. The evaluation has been carried out using information cited in the literature and is presented in Chapter 2.

Insight gained from the completion of the literature review has been combined with farmer experience, product safety and erosion expertise to produce a soil management strategy. The details of this strategy and its application to the field are described in Chapter 3. Strategy performance in soil and water conservation is quantitatively assessed at the plot scale, in Chapter 4 where it is directly compared with conventional soil management.

Experiments to help identify the most suitable cover management treatment are described in Chapter 5. This work includes an assessment of herbicide and dose effects on plant and soil physical properties and the subsequent implications for soil erosion potential. Conclusions of the research and recommendations for further work can be found in Chapters 6 and 7.

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## **2. Understanding the issues**

Before significant progress can be made in the development of any new management approach a clear understanding of the pertinent issues must be reached. As the first aim of this thesis is “to contribute to the development of a soil conservation strategy for use in Mediterranean viticulture,” it is essential that the issues which surround soil erosion and vine cultivation in this region are reviewed. This review has been carried out using information cited in the literature and on-site observation. It explores how grapevine physiology and growth requirements have influenced where and how vines are cultivated on a commercial scale, and the impact this has had on soil management and erosion. It also explores existing soil conservation techniques and their compatibility with established vineyard plantations. The author’s evaluation of the present situation is in the final section of this chapter.

### **2.1. The agronomy of viticulture, vine physiology and growth requirements**

#### **2.1.1. Cultivation**

*Vitis vinifera* L. is a member of the Vitaceae family, which are dicotyledonous angiosperms. It is a woody, perennial liana with pressure sensitive tendrils and in the wild it is found in deciduous forests, where its flexible trunk and branches are supported by the trees on which it grows. It is a temperate-climate species, which is unable to withstand extreme winter cold and it requires long, hot and dry summers for the maturation of its fruits (Mullins *et al*, 1992; Pearson & Goheen, 1994). Under humid conditions, the plant becomes extremely susceptible to fungal and insect pest attack (Winkler *et al*, 1974).

The origin of *Vitis vinifera* L. cultivation (viticulture) lies in the Neolithic era (6000 – 5000 BC) on the eastern shores of the Black Sea, in the region known as Transcaucasia. It is thought to have been initiated by the accidental discovery of wine, which would have resulted from the storage of grapes gathered from the surrounding forests (Mullins *et al*, 1992).

It was the Phoenicians and Greeks who introduced viticulture to North Africa, Sicily, Southern Italy, Spain and France in the first millennium BC but it did not become

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widespread in France until the establishment of the Roman province of Gallia Narbonensis in the first century BC. By 300 AD, the practice had become widespread throughout Europe and today, it is mostly found between the latitudes of 30°N and 50°N and between 30°S and 40°S (Jackson & Schuster, 1987; Mullins *et al*, 1992). Most of the commercial vineyards are found between sea level and 1,000 feet (Winkler *et al*, 1974).

Grapevines do not breed true from seed and thus changes to plant productivity and pest resistance have been the result of changes in husbandry. One such example of this is that, in its wild state, the grapevine produces large numbers of small bunches of fruit. As a crop plant however it is severely pruned to reduce the number of bunches and encourage an increase in fruit size and quality. If carefully tended, grapevines can remain productive almost indefinitely but in commercial viticulture, they are seldom retained for more than 40 years. This is because the level of productivity reduces with age (Mullins *et al*, 1992; Winkler *et al*, 1974).

Vegetative propagation is necessary to conserve the subtle gene combinations present in traditional grapevine cultivars and nearly all grape varieties, whether for fruiting or root stocks, are propagated by cuttings (Mullins *et al*, 1992; Winkler *et al*, 1974). In propagating the vine from a cutting instead of a seed, the root development is altered significantly.

Whereas a vine grown from seed develops a taproot system with a major axis which gives rise to secondary roots, a vine grown from a cutting has a more highly divided root system (Figure 2.1). The main framework roots (6 – 100 mm in diameter) are usually found at a depth of 30 – 35 cm from the soil surface and their number is said by Richards (1983) to remain constant after their third year. Smaller, permanent roots (2 – 6 mm diameter) grow from this framework and they either grow horizontally (spreaders), or they grow downwards (sinkers). These roots undergo repeated branching to produce the fibrous or absorbing roots, which are ephemeral and are continually being replaced by new lateral roots (Richards, 1983). Although ‘sinker’ roots do penetrate to considerable depth, fibrous root, which accounts for the major portion of the root mass, is found primarily within the top 20 – 50 cm (Mullins *et al*, 1992, after Champagnol, 1984).

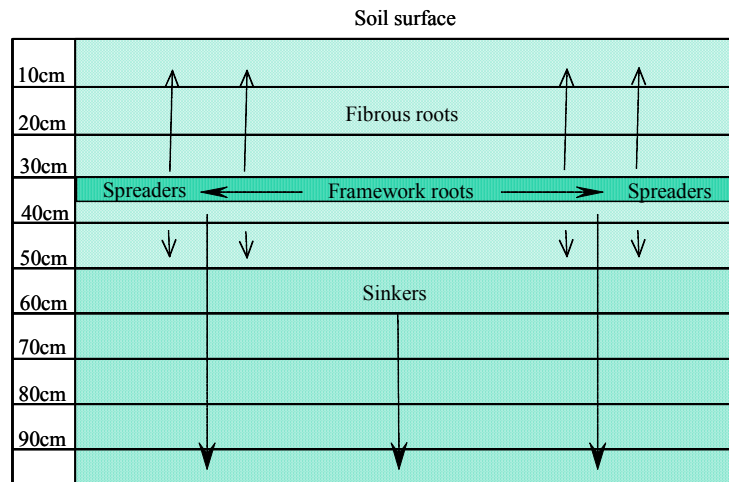


Figure 2.1

*The main zones of root exploitation by a vine propagated from a cutting  
(Based on the description given by Mullins et al, 1992)*

Depth of root penetration is very much dependent on the presence of obstructions such as hard pans or a water table but soil type also plays an important role. According to Winkler *et al* (1974), not many roots will be found below 8 – 12 ft (2.4 – 3.7 m) in sandy loam soils, 5 – 8 ft (1.5 – 2.4 m) in loams, or 2 – 3 ft (0.6 – 0.9 m) in clays. Overall, more than 70% of vine roots are found in the top 1m of the soil (White, 2003).

By increasing the level of reticulation in the rooting system, structural stability of the soil in which the vines grow is improved and its susceptibility to erosion by water is reduced. However, by bringing the main zone of exploitation of water and nutrients nearer to the soil surface, vines which are grown from cuttings will experience greater sensitivity to soil management practices than those which are grown from seed.

In 1868, the grape root pest *Phylloxera* (*Daktulosphaira vitifoliae* (Fitch)) arrived in France and spread rapidly throughout Europe. The results were catastrophic as more than 9/10 of the vines in France alone were destroyed. Since then, cuttings have been grafted on to an American rootstock, which is resistant to *Phylloxera* (Pearson & Goheen, 1994; Mullins *et al*, 1992; Jackson & Schuster, 1987 and Winkler *et al*, 1974). The same approach has been used in some circumstances to introduce resistance to nematode attack.

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When cuttings are planted, the main roots at the base of the cutting are placed below the depth of the plough so that they do not get damaged during cultivation. Most cuttings are between 12 and 18 inches (30 – 45 cm) in length and the portion which protrudes above ground should be covered by a mound of loose earth of approximately 2 inches (5 cm) depth. This earth cover prevents the vine from drying out before it has had a chance to establish (Winkler *et al*, 1974). However it also provides an obstacle for surface water flow which can lead to the incision of channels in the soil surface.

Commercial plantations are set out in rows to facilitate their management. Before the vines start to bud in the second spring, a single furrow is turned along and away from each side of each row. This procedure exposes suckers and surface roots which need to be removed (Winkler *et al*, 1974); however, on sloping land, it is also likely to contribute to accelerated soil loss by encouraging the concentration of surface flow.

In the Middle East, cultivated grapevines are often grown along the ground but viticulture in Europe, America and Australasia, has been based either on small, free standing bushes or on the training of vines on supports. Traditional Roman practice was to use live Poplar trees to provide support (Mullins *et al*, 1992). These living supports would have provided additional soil anchorage through their rooting habit and the ground surrounding them would have been used for pasture or for growing bell beans (Ingles *et al*, 1998). The presence of a complete vegetative cover would have provided substantial protection for the soil against the forces of rain splash and runoff.

Some examples of Poplars as vine supports can still be seen in Northern Italy today, but in the majority of cases, these have long since been replaced by short-term supports (for cultivating vines as free standing bushes) or permanent trellises made of posts and wire. This development has stemmed from improved knowledge of the effects of planting density, canopy manipulation and pruning on productivity and fruit quality, as well as incentives for increased production.

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The accumulation of information over many centuries on the relationship between vines and their environment has contributed to many of the present day customs and regulations. On the July 30<sup>th</sup>, 1935, the *Institut National des Appellations d'Origine* (INAO), a branch of the French Ministry of Agriculture, was created to manage the administration of the process for wines and many other European countries have since adopted this approach. The Appellation d'Origine limits the production of certain types of wines to recognised wine districts. In most cases, it specifies which cultivars are to be used and the planting density. Wines produced under these controls are referred to as Vin de Pays.

Those wines which carry the Appellation Controlée label have undergone even stricter controls. The main restrictions include the yield of the wine (litres per hectare), the maximum and minimum alcohol content, the grape varieties and their composition in the vineyard, pruning method, the use of fertilisers, the time of harvest and other factors relevant to wine quality (Mullins *et al*, 1992; Jackson & Schuster, 1987). Many farmers vie to meet these regulations so that they can achieve a premium price for their wine. Wines produced under conditions which have not met with the regulations can only be sold as Vin de Table, and as such, they are worth significantly less. Although these regulations ensure the production of good quality wines, they can often impede change and this has implications for vineyard soil management.

#### *2.1.2. The main stages of vine growth*

The grapevine has two growing seasons involved in fruit production and thus it carries two crops at any one time. The first season sees the development of the flower clusters or 'buds'. This process takes place within the green shoots on which the current crop is flowering and maturing. After the harvest, the green shoots, which contain the buds, drop their leaves and become brown canes. Root development continues for a short time before the vine enters a period of winter dormancy (Erb *et al*, 1998).

The stages of shoot development in the second season are many and varied and Pearson and Goheen (1994) present two interpretations: Eichhorn and Lorenz (1977) identified 47 stages, from winter dormancy to the end of leaf fall. Baggiolini (1952) identified just ten of those stages but stopped at fruit set. Overall, the phenological

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events which are of greatest importance in viticulture and pest control are dormancy, bud break, inflorescences clearly visible, anthesis or bloom, fruit set, veraison, fruit maturation and leaf fall (White, 2003; Mullins *et al*, 1992).

Under Mediterranean climatic conditions, dormancy is broken and the second growing season is initiated once the vine has been exposed to a certain number of chilling units (hours below a certain temperature) (Mullins *et al*, 1992), the soil has thawed and the air temperature has reached 5°C. The previously dormant buds begin to swell and ‘bud break,’ the point at which green tissue becomes visible, ensues (Pearson & Goheen, 1994). It is at this point that the buds are at their most vulnerable to frost damage but in areas where spring frosts are known to be a threat, bud break can be delayed by late pruning and losses can be avoided. The vines which are most susceptible to frost problems are those situated in low lying areas or hollows. Vines grown at higher elevations and on slopes are usually unaffected as the cold air will sink to the bottom of the slope (Battany & Grismer, 2000; Erb *et al*, 1998).

According to the review carried out by Mullins *et al* (1992), there are several environmental factors which are known to influence inflorescence (flower cluster) development and these subsequently influence the fruiting potential of the vine. Response to temperature varies between cultivars but in general, the higher the temperature during the first season of growth (the bud development phase), the greater the number of inflorescences produced. In the second growth season, too much shading of the buds by foliage in late spring can limit inflorescence development. This implies that light intensity plays a role which is independent of temperature.

The review by Mullins *et al* (1992) also shows that there is controversy over the influence of water stress on the fruitfulness of latent buds. Some researchers believe that lack of water depresses fruitfulness. Others believe it improves it, by limiting foliage development and allowing greater light penetration into the canopy. From this we can deduce that the effects of water stress on bud development are closely intertwined with those of light intensity. Once the inflorescences have emerged and come into flower, the vine’s demand for water is increased and it becomes very sensitive to water stress (Oliviera, 2001).

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Anthesis or ‘bloom’ is the point at which pollination of the flowers takes place. This usually occurs in late May or early June (Erb *et al*, 1998). Depending on the cultivar, there can be up to three inflorescences per bud and each inflorescence may contain one thousand flowers. Only 20 – 30% of these flowers develop into berries, undergoing a process known as fruit set. The remainder shrivel and die. The berries which have set, start to grow but many of these are later dropped in a process known as ‘abscission,’ which can be increased in response to environmental stresses such as a lack of water (Mullins *et al*, 1992).

For the first three weeks of berry development, growth is through cell division but this is later replaced by osmotically driven cell enlargement. Between mid July and mid August, veraison begins (Erb *et al*, 1998; Pearson & Goheen, 1994). This is the point at which the berries start to ripen and change colour and the vine’s sensitivity to water stress is increased (Oliviera, 2001). One process which occurs during ripening is the concentration of sugars in the berry. This sugar content has an important influence on the quality of the wine produced from the grapes, as it will determine the alcohol content. A sudden increase in soil water availability from the onset of veraison to maturity and harvest can therefore have a detrimental impact by increasing the yield and reducing the quality.

The majority of vineyards in the Mediterranean region are rain fed. As such, the timing, placement and volume of water being applied to the soil are beyond the control of the farmer. To make the best use of the rain which falls and avoid sudden fluxes in soil water availability to the vines, it is necessary to control the way in which water is distributed within the soil mass. Introducing management techniques which influence soil structure is the only means by which this can be achieved.

Senescence and abscission of grapevine leaves tends to occur in October. Unlike most perennial crops, only a small proportion of the mineral content of the senescing leaves is translocated back into the trunk and roots before abscission takes place (Mullins *et al*, 1992). The leaf litter has to decompose before the nutrients are made available to the vines once more and artificial inputs are often necessary because the rate of nutrient recycling is slow.

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The vegetative growth period for vines in a temperate Mediterranean climate is from mid April through to late October (Pearson & Goheen, 1994). Outside this time frame, the vines are devoid of leaves and are unable to protect the soil from rain splash. Unfortunately, this absence of protection coincides with the wettest part of the year. It could be argued that even when in leaf the vines offer little protection to the soil below. It has been observed that the architecture of the leaves encourages water droplets to coalesce. The larger droplets which are formed by this coalescence can have a more damaging effect than raindrops when they strike the soil surface. Styczen & Hógh-Schmidt (1988) attributed this to the increase in drop momentum which occurs with an increase in drop diameter and thus, the subsequent increase in energy available for detachment. The degree to which this process occurs is very much dependent on how the vines have been trained.

## ***2.2. The soil erosion problem in Mediterranean vineyards***

### *2.2.1. The soil as a resource*

Soil is formed at the interface between rock, air, water and living things. It is created by interactions between living organisms and regolith, which is a layer of unconsolidated material formed on the earth's surface by the decay of exposed rock. The uppermost layers of this medium are referred to as the top soil and they have experienced the greatest degree of physical and chemical change. These are the layers in which the highest levels of activity take place and provide a large proportion of the water and nutrients required by plants for growth. The layers below this are subjected to significantly less disturbance and as such, they continue to maintain the physical and aesthetic properties of the parent material. Provided they can be explored by plant roots, these sub-soil layers can be an important source of water for plants during dry periods (Brady & Weil, 1996).

The erosion of soil and its redistribution are both naturally occurring processes which are driven by the actions of water and wind to achieve a state of dynamic equilibrium. However, the rate at which they occur is often significantly influenced by the actions of man. The removal of natural vegetation cover and exposure of the soil to the elements and mechanical procedures leads to a breakdown in structure. This leads to a loss of fertility and substantial losses of the soil itself. In many instances, it has resulted in land abandonment (Morgan, 2005).

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Much of the sloping land currently under vines is extremely susceptible to erosion by water and very little topsoil remains. A similar problem exists for land under olive and top fruit production. Garcia-Torres & Martinez-Vilela (2002), quoting from Morgan (1992), stated that “soil losses under Mediterranean agricultural conditions could reach 20 – 40 tons/hectare in a single storm and up to 100 tons/hectare in extreme events.” Thus, it is important that the mechanisms of soil erosion by water are clearly understood.

#### *2.2.2. The mechanisms of soil erosion by water and modern-day viticulture practices*

For soil erosion to occur there has to be a means of detachment and a means of transport. Where erosion by water is concerned, the agents involved in these processes are rain splash and runoff.

The energy imparted by a rain drop striking the soil surface detaches soil particles from the soil mass, directly below the point of impact, and throws them outwards. If this process occurs on a slope, more material is thrown down-slope than up-slope. The process also causes compaction and can often lead to the formation of a surface crust, with fine particles blocking the pores and cracks. The formation of such a crust significantly reduces both the surface roughness and the permeability.

Runoff occurs when the rate of rainfall or snowmelt exceeds the rate of infiltration and evaporation. This can be caused by the soil already being saturated or frozen, the presence of a soil or rock with low permeability, the presence of a surface gradient, a lack of surface roughness or a combination of any of these. The term refers to the movement of water over the soil surface and it presents itself in two main forms; sheet wash or ‘overland flow’ and channel flow.

Sheet wash, as the term implies, describes a relatively even layer of water moving over the soil surface and it has a general levelling effect. If the energy of the flow is sufficient to break the cohesive bonds which hold the soil together, detachment of soil particles occurs. The capacity of the flow to detach material is increased with velocity, or by the presence of rainfall as this causes turbulence and increases the amount of energy present.

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Transport of the detached material is also dependent on the level of energy available in the flow. When energy levels are low, only the lighter particles; the clays and silts, can be carried in suspension. When energy levels are high, the heavier sand particles can also be transported. As flow rate reduces, the ability to carry material in suspension also reduces and deposition occurs.

Flowing water will always take the path of least resistance. Where features which cause an obstruction are present, the flow will be diverted and become concentrated. This concentrated flow will also occur where depressions exist, such as the gaps produced between soil clods when the ground has been cultivated or in an area of compaction. When a channel is developing, the up-slope end known as the ‘head wall’ will retreat causing the channel to extend in an up-slope direction. At the same time, the concentrated flow of water will cut down through the soil profile until it reaches a layer of resistance (refer to Figure 2.2). Those channels which can be removed by weathering or cultivation are termed rills and those which are much more substantial and permanent are termed gullies.

Once gullies have developed to the point at which they can no longer be traversed by machinery, the land may have to be abandoned if there is no alternative means of access. In an agricultural context this has severe economic implications for the farmer as both the land value and the farm’s productivity are reduced.

Channel flow has a greater erosive capability than sheet wash (Morgan, 2005). This is because there is less resistance imparted by the soil surface in a channel situation and this enables greater flow velocities to be attained.

A soil’s potential to erode is influenced by many factors but the main ones are texture, structure, moisture content and exposure. Soil texture is determined by the proportions of sand, silt and clay which are present (Brady and Weil, 1996). In general terms, the presence of clay increases cohesion and improves total shear strength. When dry, a soil with high clay content is at its strongest; however, as moisture content is increased the cohesive bonds between the soil particles become severely weakened and they may even reach the point where the soil begins to flow like a liquid (the liquid limit).

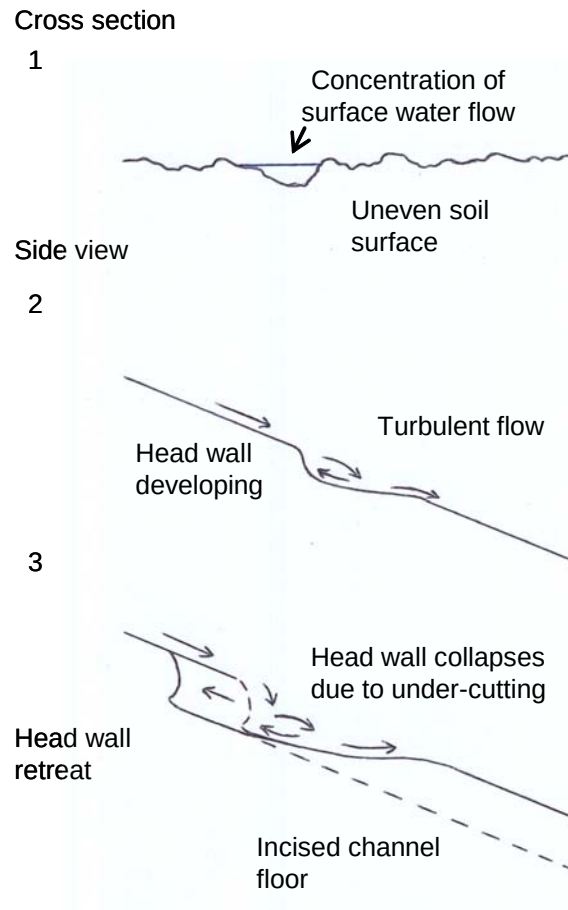


Figure 2.2  
Channel formation

The way in which the sand, silt and clay fractions have been aggregated determines the soil's structure. The presence of a 'good' soil structure; one which is granular or crumb-like, can help to defer the weakening process by improving the infiltration capacity of the soil and thus reduce the length of time it is exposed to wetting. 'Good' structure can also reduce the occurrence of 'slaking,' which is the collapse of aggregates caused by the entrapment of air under rapid wetting.

Structure is improved by the incorporation of organic matter by micro and macro-organisms and by the action of plant roots. In addition to this, substances exuded by both the organisms and the roots and the presence of the roots themselves combine to improve soil strength. If the soil surface is left exposed, it is subjected to the actions of structural breakdown by rain splash and runoff and consolidation occurs. Vegetation can therefore play an extremely important role, not only by improving soil

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strength and soil structure but also by absorbing the energy imparted by rainfall, increasing surface roughness and reducing flow velocity (Morgan, 2005; Roose, 2002; Llewellyn, 1999; Coppin & Richards, 1990; Chisci & Morgan, 1986; Duley, 1939).

After the Phylloxera attack of the 1860's and 70's (section 2.1.1) and until 1980, viticulture in Europe underwent a period of sustained growth and the supply of wine was far in excess of demand. In the early 1970s the French government recognised that something needed to be done to bring the level of production under control and improve the quality of the wine being produced, so they launched 'Plan Chirac.' This 'Plan' offered farmers subsidies to grub up entire vineyards and change the varieties which were grown in others.

Throughout the rest of Europe, overproduction and poor quality produce continued to be a problem, so 'Plan Chirac' was extended to the whole of the European Union, under the new name of 'regulation EEC 1163/76' (Sheahan, 1996). These measures significantly reduced the area of land under vines but their effectiveness at limiting production was later curtailed by a change in the rules and the funding. After 1990, production increased once more but the total land area devoted to viticulture remained unchanged. This was achieved by transferring much of the production to regions which were better suited to the purpose. (Pla Sentis *et al*, 2005; Dutruc–Rosset, 2002). The favourable growing conditions of the Mediterranean resulted in a substantial increase in the amount of land dedicated to viticulture.

In order to facilitate this increase, the Mediterranean viticulture industry underwent many changes. The majority of these changes were driven by economics and little thought was spared for the environmental impacts. The result has been a dramatic change in both the appearance and the hydrology of the landscape (Oliveira, 2001).

A large proportion of the manual work traditionally associated with viticulture has been replaced by machinery. Narrow tractors, which are capable of driving in between the vine rows, are now a common feature and in some instances, mechanical harvesters which straddle the vine rows are used. Vehicles used for working on the shallow slopes are equipped with pneumatic tyres and those for use on steeper slopes are mounted on tracks for improved traction. In order to facilitate the use of this

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machinery, fields have been made bigger, often by the inclusion of more marginal land. On steep slopes, the majority of the terraces have been removed because they are expensive to maintain and plantations have been realigned up-slope down-slope. In many instances, plantations run the whole length of a hill slope without the intervention of a hedge, a buffer strip or a ditch. Such conditions give rise to extremely high surface water flow velocities, thereby increasing the amount of energy available for soil detachment and transport.

To compound the situation further, on sloping land the soil in the inter-rows is kept bare by regular cultivations using spring tines, which cause disturbance to a depth of 25 cm. The farmer's motive for this is to encourage infiltration of rainfall into the vine root zone and to prevent frost damage and competition for water and nutrients during critical periods of vine growth (Amadiou and Treil, Pers com, 2001). Whilst tillage does initially increase the infiltration capacity of the soil, by increasing the surface roughness and the number of macropores which are present in the surface layer, the effects are short-lived. This is because there is no protection from rainfall and the rate at which soil organic matter is mineralised under Mediterranean conditions is also increased by cultivation (Basch *et al*, 1998), through the exposure of new surfaces to microbial activity and through increased aeration. This reduces the soil's structural stability and results in collapse on wetting. Degeneration of the soil surface results in the formation of a seal or crust, which reduces its hydraulic conductivity, thereby increasing the potential for runoff and erosion to occur (Ramos *et al*, 2000; Louw & Bennie, 1991).

White (2003) and Farkas *et al* (2002), state that in dry conditions, shallow cultivations can be beneficial to the retention of water in the soil layer below, by reducing evaporative losses through the disruption of the soil's hydraulic conductivity. Whilst in general this may be the case, the proportion of the water which is available for uptake by plant roots is limited by the continuity and stability of storage pores within the root zone (Rowell, 1994). In poorly structured soils, pore continuity and stability is reduced and soil water is less extractable by plant roots as a result. This scenario will arise even when the soil is very wet. Soils which have a high clay content, in addition to poor structure, are also prone to cracking at depth. This encourages bypass flow to occur, which is when the rainwater is taken down below the root zone, making

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it unavailable to the vines. The rooting activity of a living cover increases the continuity and stability of soil pores and reduces the amount of cracking by helping to improve soil structure. This improves soil water distribution and availability within the root zone (Crecimanno & Provenzano, 2002; Rowell, 1994). Soil water loss as a result of transpiration can be managed during dry spells by inhibiting the growth of the plant cover.

It has already been established that the threat of frost damage is reduced on sloping land and can be managed by pruning (section 2.1.2). Any weeds which may cause competition for water and nutrients may be controlled at sensitive times in the vine growth cycle either by mechanical mowing or through the use of a herbicide.

Although perceived as a valuable procedure in viticulture, the published facts show that the real value of regular cultivation is extremely limited and the practice is destructive and impractical. It causes substantial weakening of the soil structure, it is considered an erosion process in itself (Govers *et al*, 1994), it can only be done when the ground is in a trafficable state and large labour and energy costs are associated with it. During long storm periods, which prevent re-cultivation, severe channelling of the surface can occur. This can leave the vines clinging to a narrow ridge of soil or even cause them to fall over and die (Plate 2.1). Greater benefit can be attained by employing other methods of soil management.

Many farmers are aware of the soil loss problem which results from their activities because they are losing substantial areas of land and regularly face costs for clearing plantation access roads and ditches. Unfortunately, the majority accept these costs as being an inherent part of vine production. Some may carry out an element of repair work but few consider taking measures to prevent the problems arising. As a producer of wine, their main focus is on the health of the vines and the quality of the harvest.



*Plate 2.1*

*Severe erosion of the inter-rows leaving vines clinging to narrow ridges of soil – Vaucluse, France  
(Ceri Llewellyn, February 2003)*

### ***2.3. Existing soil conservation techniques and their compatibility with Mediterranean viticulture practices***

From a land capability perspective, much of the land currently under viticulture should be taken out of production and protected whilst being allowed to revert to its natural state. This is because its present use is unsustainable. Unfortunately, because of the high economic dependence and social consequences, this is unlikely to happen unless there are substantial changes in the law, which are policed, and / or a financial incentive is made available. Thus, protective measures need to be implemented which will fit with the present land use.

Measures available for protecting soil from erosion by water on sloping land generally split into two categories: mechanical and biological. They are described as branches of engineering and can be used either individually or in combination, depending on the environmental conditions, erosion risk and the proposed or existing land use.

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### 2.3.1. Mechanical engineering techniques

Mechanical engineering, as the name implies, involves the use of structures and depends on physical manipulation of the surface topography to control the flow of water. Methods in this category do little to minimise detachment but are often very effective in controlling the subsequent transport of soil material. A multitude of techniques exist (Morgan, 2005), however, there are only two which are compatible with intensive viticulture. These are contouring and bench terracing and they both work by altering slope gradient and slope length to reduce surface flow velocities to a non-erosive level.

Contouring refers to the planting and execution of all cultivation procedures across the slope. Assuming that tillage is used to maintain the surface in a weed free condition, the across-slope ridges and furrows, created by the spring tines, will increase the surface roughness and behave like miniature retaining walls. Unfortunately, this technique is only suitable for use on very gentle slopes. In the absence of additional soil conservation measures, Morgan (2005) puts the effective limits at 1° on slopes no greater than 180 m long and 8.5° on slopes no greater than 20 m long. In addition to the slope angle and length restrictions, contours can be easily damaged and fail under high intensity rainfall or from a build up of hydrostatic pressure. Thus, contouring is not ideal for use on Mediterranean hillsides.

Bench terracing is a much more stable system than contouring and can be used on slopes up to 30° (Morgan, 2005). As such, it was once a common feature of the Mediterranean landscape (Reynes *et al*, 2002). The benches are a series of soil steps which are aligned perpendicular to the direction of slope (Plate 2.2). The step dimensions are related to the natural angle of the slope and they need to be carefully calculated to ensure that they alter the slope profile sufficiently to cope with the anticipated surface flow rate.



*Plate 2.2*

*An example of bench terracing on a Mediterranean hillside – Murcia, Spain*

*(Jane Rickson)*

The risers, or vertical front walls of the benches, are often very steep, so they are commonly planted with grasses and reinforced with stone to improve their stability. The bench shelves, or upper surfaces, are carefully graded so that water is encouraged to flow towards the hillside, thereby increasing its retention time on the slope. If the grading or the dimensions of the steps are inadequate, then severe breaching of the structures can trigger a mass transfer of material downhill. The surcharge created by an increase in the soil moisture content can have a similar effect and the resulting soil losses are often far greater than those from slopes which have not been terraced (Morgan, 2005).

Although bench terracing can be extremely effective in viticulture, it is expensive and cannot always be economically justified by the farmer (Roose, 2002). Installation and maintenance require a great deal of skill and labour and this increases the production costs. Planting density and productivity may also be affected as slope angle determines the bench shelf dimensions and thus the number of rows which can be installed. Some mechanisation of crop management is possible in a terraced system but procedures are limited by the width of the benches. Approaches which are more sympathetic to, yet still improve, the existing plantation system are more likely to be accepted.

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### 2.3.2. Bioengineering techniques

Bioengineering focuses on the role of vegetation and surface applied materials to protect the soil from rain splash and surface flow. It therefore has an influence on detachment and transport (Morgan, 2005). It can also be more easily integrated with existing cropping systems because changes to plantation layout are not an essential requirement for its installation.

As with mechanical engineering, there are many bioengineering techniques. On reviewing the literature, it would appear that these techniques can be divided into three main groups:-

Those which deal

- solely with soil surface protection,
- with a combination of protection and stabilisation, and
- with a combination of stabilisation and reclamation.

Only techniques which fit into the first two groups will be discussed here, as maintenance of the land in a productive state is the key interest.

Mulching is the application of a layer of material to the surface of the soil. In all cases, this layer will provide a degree of soil protection although the level of effectiveness, its longevity and additional benefits will be very much dependent on the material used. Choice of mulch is often limited by tradition and what is available locally.

Nachtergaele *et al* (1998), refer to the use of gravel as mulch in the vineyards of southern Switzerland. This is an ancient practice which can take up to three years to install. The soil is initially ploughed to a depth of 80 cm to “destroy the original grassland.” A crop such as maize is then grown, chopped and incorporated in the soil at the end of the season. After rolling the soil and covering it with a layer of manure, gravel is applied to the surface in a layer which is 20 cm deep. The vines are then planted in the spring. The farmers who practice this method say that it can last up to 50 years without the need for maintenance.

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Li (2003) discusses use of the same method in the semi-arid Loess region of North West China for the cultivation of melons, vegetables, fruit trees, beans, wheat, cotton and millet. In this region, the method has been used for more than 300 years to reduce the evaporative loss of soil water, as the rainy season does not coincide with the growing season for most crops and water is scarce. When the productivity of the soil starts to decline, the mulch is removed and the soil is left exposed to weathering for several years before it is re-prepared for mulching.

In addition to soil protection and reduced evaporative losses, the gravel is reported to increase the load bearing capacity of the soil, help suppress weeds and protect the vines from frosts; by minimising the diurnal fluctuations in soil temperatures (Li, 2003). Mulches are said to generally reduce soil temperature, thereby reducing the length of the growing season (Morgan, 2005). This may in turn delay budburst until the hazard of frost has passed.

Nachtergaele *et al* (1998) imply that the quality of the wine can also be improved using a gravel mulch. This is because the grapes receive additional radiation which is reflected from its surface.

Although successful in Swiss vineyards and on the Loess Plateau, obtaining sufficient quantities of gravel to mulch many Mediterranean vineyards is likely to prove difficult and extremely expensive. In addition to this, the method is designed to be implemented at the plantation establishment phase. If carried out post-establishment, vine roots may be damaged and it will be difficult to apply the mulch to the vine rows.

Experimental work conducted by Poesen and Ingelmo-Sanchez (1992) identified that rock fragments can both increase and decrease inter-rill erosion and runoff losses. They believe that the outcome is determined by the positioning of the fragments in relation to the soil surface and the influence which this positioning has on the soil's structural stability and macro-porosity. In the reporting of this work, Poesen and Ingelmo-Sanchez (1992) also state that rock fragments can be readily transported when present in areas of concentrated flow. For these reasons, the author does not recommend the use of rock fragments for erosion control.

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When applied at a rate of  $5 \text{ t ha}^{-1}$ , straw mulch has proven to be extremely effective at reducing soil losses on a number of different soil types and slope angles of  $6^{\circ}$ - $7^{\circ}$  (Morgan, 2005). Performance on steep slopes is not known. Gril *et al* (1989) tested the effectiveness of a number of different mulches in a Beaujolais vineyard using a rainfall simulator. Straw mulch was found to provide good protection but results could not be extrapolated to the field scale as the studies did not consider rill erosion. The straw is most protective if left as a surface cover but under windy field conditions, anchorage is necessary to prevent it from being blown away. Some protective benefit can be gained by incorporating the straw, as this causes it to bind with the soil matrix and simulate the effect of plant roots. This helps to avoid the anchorage problem. However, the level of protection is likely to be significantly less as the percentage of surface cover will be reduced, exposing more bare soil.

As an organic material, the mulch will readily decompose and will need to be replenished each autumn. Cereal crops are not a common feature in the Mediterranean landscape and the EC has projected a decline in production in this region (European Commission, 2005), thus, the difficulty in obtaining straw is likely to render its use impractical. The extremely high frequency of summer fires in the region and the combustible nature of the straw further limit its viability in such a situation.

By-products of the viticulture industry, such as the canes removed during pruning, are often collected at the edges of the fields and burned. On some estates the farmers have tried to make better use of this material by mechanically shredding it and distributing it over the bare soil surface as a mulch. Whilst this increases the organic matter contribution to the soil, the quantities of material available are often insufficient to provide a protective mulching effect and the majority will have decomposed before the arrival of the violent summer storms.

Although organic mulches protect the soil from structural breakdown and erosion by rainfall, their ability to reduce evaporative losses and increase soil moisture content at the surface can have detrimental impacts on the health of the crop. Increased soil water availability in the surface layers of the soil encourages its exploitation by plant roots. Absence of roots at depth will increase plant susceptibility to drought stress if the mulch is not maintained (Othieno, 1980). Increased soil water content can also

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cause poorly structured soils to turn anaerobic (Rickson, 1995). This in turn may lead to the formation of toxins in the soil.

In civil engineering projects, permeable materials known as geo-textiles are commonly used in combination with vegetation to protect soil from erosion on sloping land. They take two forms; surface applied and buried (Morgan, 2005). Those which are surface applied are mostly temporary and made from natural fibres which have been manufactured into a mat, a sheet or a loose grid which can be rolled out over the soil surface and secured with pegs. The percentage cover provided by the textile determines the level of soil protection against rain splash, runoff detachment and surface crusting and can also affect the soil's thermal properties in the same way as a mulch (Rickson, 1995). With increased protection comes increased vegetation suppression, as light penetration and emergence are inhibited. Thus, a careful balance is required if the objective is to protect the soil whilst establishing a more permanent cover. Use of geo-textiles purely as a blanket mulch is feasible but is expensive as replacement will be necessary when they start to decompose.

The fibres of these textiles can be highly absorbent, so if a dense material is used then the rate of soil saturation can be greatly reduced. However, these textiles are not able to discriminate between different event sizes and thus, the majority of rain from a small event after a dry spell will be held at the surface and lost to evaporation. Very little will penetrate the soil profile for uptake by the crop. On wetting, the geo-textile's contact with the soil is improved by the increase in its weight. This reduces the risk of erosion by surface flow at the soil/geo-textile interface (Rickson, 1995).

It is possible to drive over these materials in wheeled vehicles, which makes them suitable for use in plantations where the crops are set out in rows. However, there is a risk of the material being trapped and torn in the caterpillar tracks of vehicles which are commonly used to traverse the steeper vineyard slopes or become snagged on the machinery used to shred the unwanted canes after pruning.

According to Rickson (1995), the geo-textiles which are buried only serve to stabilize the soil, allowing vegetation to establish; they do not protect the surface in any way. Taking the form of an open honeycomb / cellular structure, they are made from

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synthetic fibres and they are designed to be permanent installations. They are extremely expensive and difficult to install, due to the level of soil disturbance required. They are therefore unsuitable for large scale, mechanised vineyard plantations.

‘Cover cropping’ is a method which can both protect and stabilize soil. It has many functions and has been described by Anderson *et al* (2001) as “the use of live vegetation cover as a spatial or temporal component in annual or perennial cropping systems to fulfil one or several purposes.” These purposes range from soil protection and improvement, to weed management and food production for livestock and humans. Choice of species, timings and management techniques are all dependent on the objectives to be met but the basic method has been successfully employed throughout the world for many centuries.

Cover cropping has been popular in the resource-poor agricultural systems of the developing world for generating additional food, income and protecting and improving soil. Now, it is increasingly being used in industrial agriculture to improve nutrient retention within the soil. The soil’s ability to retain nutrients is determined by its cation exchange capacity (CEC), most of which is held within the organic matter fraction. Living cover provides a continuous supply of ephemeral roots, root exudates and leaf litter which are broken down by earthworm and microbial activity and increase the organic matter content of the soil. This increase improves the soil’s cation exchange capacity and its ability to retain nutrients, which reduces the need for inorganic fertilizer applications and their associated cost (Anderson *et al*, 2001; Brady and Weil, 1996).

Records show that cover cropping was a common feature of vineyards in Roman times (Ingles *et al*, 1998; Mullins *et al*, 1992) but its use in vineyards throughout the world has altered with time. This has been partly due to changes in the scale of production and changes in agricultural technology.

In the early 1900s, cover crops were sown in Californian vineyards to reduce erosion and improve soil condition and fertility. Legumes and cereals were commonly sown in the autumn and mowed or incorporated with discs in the spring. This practice was

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largely abandoned in the 1940s and 50s as conventional agriculture came to rely on artificial inputs. However it was later revived in the 1980s with the availability of new cover species, implements and techniques and a growing interest in sustainable agriculture. In 1998, approximately 16% of Californian vineyards were planted to cover crops other than resident vegetation (Ingles *et al*, 1998).

Cover cropping is also used in the vineyards of Australia and South Africa. Whilst it has not been possible to trace the history or the scale of its use in these countries with the available literature, the current drivers appear to be governmental pressures for environmentally sustainable production and improved field working conditions. For both of these countries, planning regulations are in place to restrict the location of new vineyard installations and farmers are guided to plan vineyard layouts so that they will not contribute to soil erosion (South African Wine and Spirit Board, 2004; Water and Rivers Commission and Department of Environmental Protection, 2002).

Permanent vegetation cover which is managed by mowing can be seen on a small proportion of the vineyard floors in the Mediterranean region. However, it has been noticed by the author that the practice is limited to plantations in the valley bottoms, where the slope is negligible and there is little erosion risk. In such locations, the soil is often deep, fertile and wet, thus it is believed that the cover is deliberately installed and managed here in a way which creates competition for resources. This would help to reduce vine vigour and produce higher quality wine. If vigour reduction is the only purpose for which the farmers in this region have used cover, it is quite possible that they are not aware of how changes to cover management can also increase soil nutrient and water availability and the additional benefits that can be found from its use on sloping land. This would support the farmers' reasoning for regular cultivations given in section 2.2.2.

#### **2.4. An evaluation of the present situation**

In recent decades, there have been a number of published experimental trials on the use of cover crops in vineyards for erosion control. Some of these have involved the maintenance of a permanent cover and have been found to cause competition (Colugnati *et al*, 2003; Leonard, 2001; Dalbo & Becker, 1994; Gril *et al*, 1989 and Van Huyssteen & Weber, 1980). Others have involved chemical or mechanical

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destruction in the spring to prevent competition (Bovio *et al*, 2002, and Morlat, 1981), however, these limit soil structural improvement and necessitate re-establishment each autumn.

Only a few studies have considered selecting species based on growth characteristics which are complementary to the requirements of the vines, such as those which are:

- naturally less competitive for water and nutrients during the summer but more aggressive in autumn,
- low growing,
- provide weed control,
- are capable of growing in the local conditions and
- for which seed is commercially available (Delabays *et al*, 2000; Gaffney & Van der Grinten, 1991, and Klik *et al*, 1998).

Although this option would seem the most appropriate and would have the lowest management costs, it will not always be possible to find a mixture of species which meet the first and the last two requirements. Whilst little can be done to alter the environmental conditions in which the cover is required, or to improve the availability of seed, it may be possible to limit nutrient and water uptake by the cover during sensitive periods in vine growth by using a low dose of herbicide. To date, no work has been found on the use of herbicides in such an application. Its potential will therefore be explored as part of a soil management strategy for use in vineyards in the following chapters of this thesis.

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### ***3. Strategy development and implementation***

#### ***3.1. Identifying the approach.***

Having gained an understanding of the cause and scale of the vineyard erosion problem, this chapter focuses on the development of a possible solution; a soil conservation strategy which is suitable for use in Mediterranean viticulture.

To meet with the aims of the project which were discussed in Chapter 1, the proposed strategy must employ bioengineering techniques (section 2.3.2). It should also be an economic and environmentally viable alternative to existing soil management practices. Implementation must therefore be possible in established plantations with minimal capital investment and maintenance costs and have limited impact on the primary crop.

It is commonly understood that if widespread change in cultivation methods is to be accepted then farmer involvement in method development is extremely important. Moreover, the potential benefits of implementing the new methods must be visible to the farmer in order for him to consider the changes to be worth the investment. The presentation of these benefits is best achieved through simple demonstration in the field. Implementation of both conventional and alternative treatments side by side will enable the observation of agronomic and economic effects on a large scale over a number of years.

Figure 3.1 illustrates the dynamics involved in the strategy's development, whilst sections 3.2 and 3.3 detail the individual stages followed from conception to field application. They are the product of much collaboration between the author, the farmers and Syngenta product safety experts, combined with the information presented in Chapter 2. Each section has been presented in a form which clearly explains the decisions reached, the working procedures used and the field conditions experienced at the time.

The emphasis of this study has been directed towards the field application of the strategy and the technical issues encountered. Whilst the costs associated with the strategy have been considered, a detailed economic analysis falls beyond the remit of this thesis.

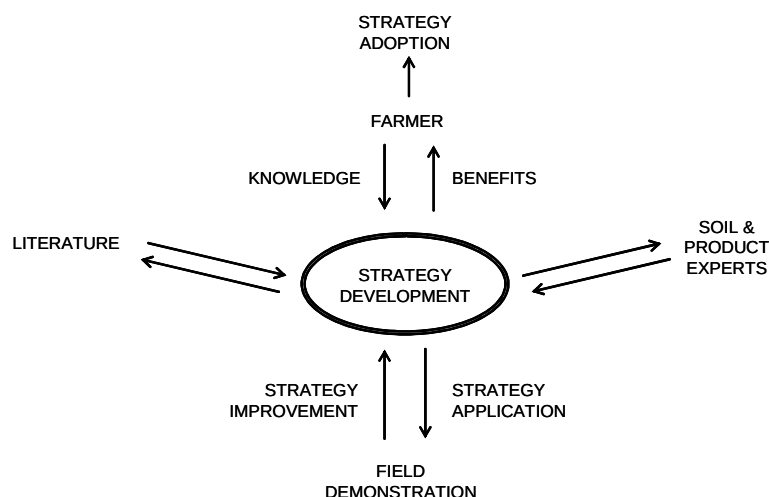


Figure 3.1

*The dynamics of strategy development following the identification that a problem exists*

### 3.2. Laying the foundations.

#### 3.2.1. The plantation system

One of the most common plantation systems in Mediterranean viticulture is also the most susceptible to soil erosion by water, so it is on this system that the soil conservation strategy will be focussed. Oliveira (2001) refers to it as the *German method*, but it can be better described as the cultivation of vines in rows, which are a tractor width (2 – 2.5 m) apart, in an up-slope – down-slope orientation.

It has been observed that this system is used on an extremely broad range of slope angles – some in excess of 18°, and on a variety of slope lengths – some greater than 150 m. The soil is often in a very poor structural condition and exhibits a low load bearing capacity under moist conditions. Nutrient status is also frequently poor which can have a negative impact on the vines.

Under *Conventional* management, soil within the vine rows remains uncultivated and is kept bare through the use of herbicides. In the inter-row areas the soil is cultivated

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to a depth of 25 cm, up to 6 times during the spring and summer months, using winged tines. Both the purpose and the limitations of this cultivation have already been discussed (section 2.2.2).

### 3.2.2. *Choice of soil management tool*

It was established in section 2.3.2 that the development of a permanent vegetative cover is one of the most suitable means of protecting the soil in an existing plantation environment. However, in order to have minimum impact on the vines and be accepted by the farmers of the Mediterranean region, careful consideration must be given to the choice of species, their management and their long term effect on soil condition.

Use of grasses is preferable to broadleaved plants, as the species present within the sward can be more easily managed. Grass cover also has more permanence and the rooting structure is more fibrous and thus, provides greater soil stability and benefit to soil health. Whilst grasses are relatively shallow rooting and therefore prone to drought induced dormancy, this normally occurs after the water sensitive period of vine anthesis. If the right cover is chosen, it may be possible to manipulate the growth cycle to complement that of the vine by artificially inducing dormancy prior to anthesis using a herbicide. This would have significantly lower associated energy and labour costs than mechanical mowing or cultivation and it should only need to be done once per year. Chemical management of a permanent grass cover is thus the chosen *alternative* soil management strategy to *conventional* practice within this thesis.

### 3.2.3. *Species selection*

Use of a mixture of species with different above and below ground growth habits helps to maximise sward development for soil conservation. In the long term, it is important that the cover is formed of perennial species which are low growing and slow growing, such as fescues (Gaffney & Van der Grinten, 1991). This is to avoid the need for re-sowing each autumn or waiting until after the seeds have dropped before applying a herbicide to inhibit plant water and nutrient uptake. By their very nature, such species are also extremely slow to establish and a more vigorous ‘nurse’

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species is necessary to help protect the soil whilst these slower growing species are emerging. English rye grass is commonly used to fulfil this role.

It is important that the species selected are capable of survival in the environmental conditions in which they are to be placed. Thus, species must only be used if they can be found to be growing successfully in the local area. The seed used must also be available commercially, so that farmers are able to purchase it without difficulty, and must be sourced locally. Imported seed may not cope well in a different climate.

### *3.2.4. Cover management techniques, timings and reasoning*

#### *3.2.4.1. Installation & establishment*

The ideal field conditions for achieving good germination, emergence and cover establishment are a well-structured soil medium which is: free-draining, aerated, nutrient-rich, warm, moist and which remains open at the surface. Soil aeration and drainage can be temporarily improved using tillage equipment, such as a rotavator, and fertilisers can be applied to adjust nutrient status artificially. The fertilizer spreader can also be used to broadcast the seed, which avoids the need to purchase new equipment. If using this method, good contact between the seed and the growing medium, which is essential for germination, can be achieved by passing over the surface with a roller.

Warm and moist conditions are critical for growth which, in the Mediterranean climate, leaves two possible windows for installation: spring and autumn. Rain in summer is unpredictable and can be extremely heavy, and the winter months are too cold. For the strategy to be practical, the use of irrigation must be avoided and implementation must also fit with the viticulture calendar so as not to cause competition with the primary crop for water, nutrients and labour.

In early spring, the ground is often very damp, thereby limiting access by machinery, and estate labour is often tied up with pruning and the planting of new vineyards. As spring progresses the carrying capacity of the soil improves as it dries but the vines are also starting to grow and demands for water and nutrients are high. These factors suggest autumn installation is the better option. The window of opportunity is further

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reduced to the period after the harvest, during which labour demands are extremely high.

Depending on the soil's structural stability, rainfall after seeding may cause a crust to form on the surface impeding the emergence of seedlings. Scarification may therefore be necessary to break up this crust if emergence is poor. Although not essential, the procedure will also increase the degree of tillering in plants which have already emerged. It does this by damaging the plant's main shoots, encouraging more to be sent out from the base. The greater the number of shoots, the more protection the plant provides for the soil. Thus scarification can increase the soil conservation potential of a cover.

#### *3.2.4.2. Chemical desiccation*

Once the grasses have established sufficiently to become potential competitors for water with the vines, management is necessary to induce a state of dormancy during the spring and summer months. Use of a herbicide is possibly the most efficient way of achieving this artificially, although the most suitable product and dose rate are not yet known. From a soil conservation point of view, good cover and soil stability must be maintained throughout the dormancy period, whilst the level of desiccation needs to be high enough to prevent early recovery without killing the plants. From an environmental and economic standpoint, it is also important that the lowest amount of chemical is applied to achieve this. A review of available products suggests that Paraquat may be appropriate as:

- It is not systemic (does not enter the plant via the roots or shoots) and only desiccates the green foliage it touches.
- It kills annual weeds but woody crops and the roots of perennial plants remain unaffected. Thus it poses no threat to the vines, removes unwanted annual weeds and should not destroy the sown vegetative cover.
- It acts only where it is applied and is then de-activated within one hour, substantially limiting the exposure of non-targets and the environment in general.
- It is fast acting. Browning of leaves can occur within as little as 30 minutes and total desiccation within 3 days.

- 
- On contact with soil, it rapidly binds to clay particles, which reduces its bioavailability in soil pore water. This results in no risk to earthworms and soil micro-organisms. It is degraded by soil micro-organisms in a matter of days, into CO<sub>2</sub> and water, so product build up in the soil is prevented. (Brown *et al*, 2004).

The timing of the application will be very much dependent on the field conditions but as a guideline, it should take place in the spring, just before the vines come into flower. This is when the vine demands for water are rapidly increasing and soil water availability is decreasing. The increasingly hot and mostly dry field conditions should maintain the cover in a dormant state until the arrival of the autumn rains, at which point, it should start to re-grow. Although dormant during the late spring and summer, the cover will remain permanent and will therefore offer the soil protection all year round.

#### *3.2.4.3. Mechanical mowing*

To encourage tillering, prevent the cover from getting too long and reduce the potential for pest harbourage, mechanical mowing should be carried out once in the spring. Care should be taken not to cut the grass too short, as this will reduce the level of resistance to surface water flow, known as the roughness coefficient (Morgan, 2005). This will lead to higher runoff velocities and greater erosion potential. The appropriate height can be determined by the plant architecture and the anticipated flow depth (Coppin & Richards, 1990).

### ***3.3. Putting theory into practice.***

When a substantial part of the strategy had been developed, it was applied to a field situation. There were three main objectives to this field work:

1. to test the practicality of implementation and identify areas of the strategy requiring improvement,
2. to assess the effectiveness of the strategy at soil conservation, in comparison with the conventional soil management methods, and
3. to provide a demonstration of the strategy's implementation, management and effectiveness to the farmer.

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### 3.3.1. Site selection

Two vineyard sites were identified for the field assessment by Syngenta field trial technicians. Site 1 is located near the settlement of La Romane, in the Vaucluse département, and was selected in May 2001. Site 2 is near the village of Villarzel-Cabardes, in the Aude département, and was selected in the late summer of 2001 (Figure 3.2).

Both sites are in Southern France and were chosen on the basis of the cultivation system employed, the presence of erosion, vehicular access and land availability.

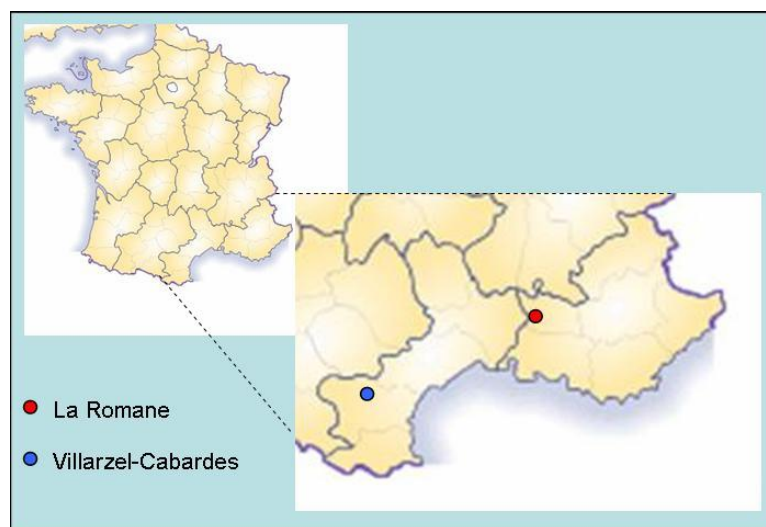


*Figure 3.2*  
*Geographical distribution of the trial sites – Southern France*

La Romane is located at an altitude of 300 m, 15 km north of Carpentras (44.19N 5.04E degrees decimal). It is one of many vast estate farms which flank the steep slopes and surrounding land of the Dentelles de Montmirail and is tended by a gang of estate workers on a daily basis. So extensive is the area under vines, that each autumn, for approximately one month, the core workforce is supplemented with migrant labour from Spain to help with the harvest. The area is influenced by a Mediterranean climate and experiences sub-tropical temperatures and rainfall throughout the growing season. Storms in this region are extremely violent and often occur during the summer months. One such example of this is the storm which hit the region on the 22<sup>nd</sup> of September 1992. 300 mm of rain fell in just over 3 hours causing widespread slope erosion and flooding (Wainwright, 1996).

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Villarzel Cabardes is a small village located at an altitude of 200 m, 12 km north-east of Carcassonne (43.28N 2.46E degrees decimal). The vineyards in this area have been established on small, gently sloping parcels of land and they are worked by individuals, who enlist local help during busy periods. Both Mediterranean and Oceanic climates influence this area and rain in summer is usually a result of localised storm activity. The region also suffers from big winter storms, such as the ones which hit between the 12<sup>th</sup> and 14<sup>th</sup> of November 1999. Rainfall of 350 mm to 600 mm was recorded and “mud flows, floods and rapid inundations took 35 lives and devastated the regional economy” (Roose, 2002).

In both of these locations, the industry surrounding wine production dominates the local economy. Accelerated soil loss can therefore lead to local disaster.

### *3.3.2. Site layout*

The vines at both sites are free standing and positioned on ridges which were formed by past cultivations and subsequent erosion of the inter-rows. As mentioned in section 3.2.1, the traditional practices kept these ridges bare through the use of herbicides, subjecting them to extensive capping by rainfall as a result. The height of the ridges varies but they served as effective bunds which isolated the surface flow of each inter-row from that of its neighbour (Plate 3.1).

At each site, an area spanning eight complete vine rows was designated as an experimental zone (Figure 3.3). The size of the zone was dependent on the vine spacing and the size of the field. This block of land was divided into two equal halves. Three consecutive inter-rows were to be subjected to conventional management practices and three were to be used for strategy development. A grassed inter-row served as a buffer between the two treatments. Key characteristics of the experimental zone at each site can be found in Table 3.1.



*Plate 3.1*

*A typical vine ridge between two cultivated inter-rows – Villarzel-Cabardes, France  
(Michel Speyer, October 2002)*

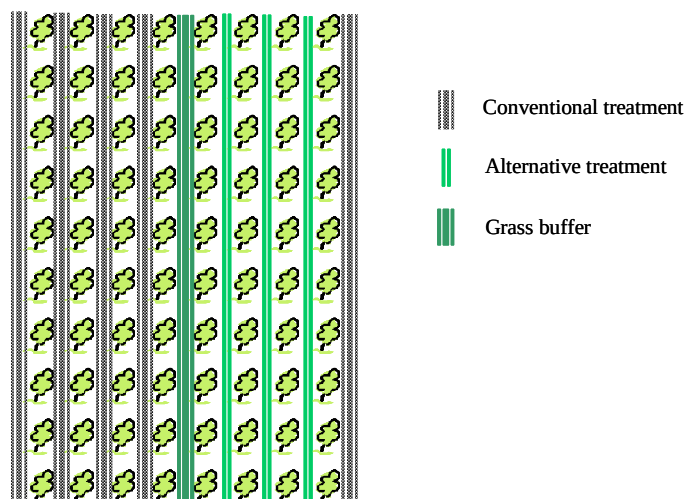


*Figure 3.3*

*Schematic illustrating the experimental zone layout*

*Table 3.1*  
*Key characteristics of the experimental zones*

| <b>Characteristic</b>              | <b>La Romane</b>         | <b>Villarzel-Cabardès</b> |
|------------------------------------|--------------------------|---------------------------|
| Slope length                       | 79 m                     | 45 m                      |
| Distance between vine rows         | 2.25 m                   | 2 m                       |
| Distance between bunds (inter-row) | 1.4 m                    | 1.25 m                    |
| Slope angle (top)                  | 8°                       | 4°                        |
| Slope angle (mid)                  | 12°                      | 7°                        |
| Slope angle (bot)                  | 13°                      | 9°                        |
| Slope direction                    | North facing             | East facing               |
| Soil type                          | Clay                     | Sandy clay loam           |
| Plastic limit                      | 24.16% gravimetric mc    | 16.84% gravimetric mc     |
| Liquid limit                       | 55% gravimetric mc       | 34% gravimetric mc        |
| Apparent cohesion*                 | 13.48 kN m <sup>-2</sup> | 6.8 kN m <sup>-2</sup>    |
| Angle of shearing resistance*      | 23.92°                   | 18.66°                    |

\* Samples were air dried, sieved to 2 mm and packed to a uniform bulk density of 1.4 g cm<sup>-3</sup>. They were then wetted to the plastic limit over a 24 hour period prior to analysis.

An automatic weather station was installed adjacent to the experimental zone at each site. Air temperature, soil temperature, relative humidity, rainfall, sunshine, wind speed and wind direction were all monitored. Each morning, the data was automatically uploaded to a secure project website, where it could be viewed by the farmers, and the French and English members of the project team.

The main purpose of this monitoring was to provide an accurate record of the conditions to which the management strategies were being subjected; to aid in the interpretation of behavioural responses. However, the data was also useful in helping to time spray applications and other vineyard management practices, thereby improving their efficiency.

### *3.3.3. Strategy implementation and evaluation*

Although the main principles behind the alternative soil management strategy remained the same for both sites, a degree of flexibility was required in its practical application to allow for differences in field conditions. In order to convey accurately the adaptations and their effects to the reader, the two sites are discussed independently.

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As the first site to be identified for the field assessment, La Romane was the first to undergo strategy implementation. This site also presented the greatest management challenge as it had the steeper slope, the greater slope length and was the most susceptible to erosion.

#### *3.3.3.1. La Romane*

At La Romane the grape harvest takes place in mid September, marking the end of a long and predominantly dry summer. Shortly after the harvest, the rains start to fall and the soil often becomes unworkable until spring. This is due to the high clay content of the soil and its propensity to retain moisture.

Following the methodology described earlier in this chapter, ground preparation of the inter-rows for sowing took place in the middle of October 2001. The timing was predominantly determined by the availability of farm labour and machinery. A first pass was made using the winged tine implement, commonly used for conventional soil management on the estate. A second pass was then made with a rotavator, which produced a granular tilth.

A commercially available seed mix (Agro Plan 20) was then broadcast at a rate of 8 g m<sup>-2</sup>. This seed mix was 30% English rye grass, 50% creeping red fescue and 20% chewing red fescue, which combine to provide a good ground cover that does not place great moisture demands on the soil (Gaffney & Van der Grinten, 1991).

When the rains arrived in late October, the soil temperature had dropped below that which is ideal for germination (approximately 10°C) and the soil surface began to seal (ref section 2.2.2). Beneath the seal, the tilth maintained a very stable granular structure and was extremely absorbent. Once saturated however, the granules became highly vulnerable to detachment and transportation by runoff and channelling started to occur.

As the soil temperatures began to increase in the spring of 2002, a substantial grass cover emerged from the sediment deposits at the bottom of the experimental zone. The channels which had formed over the winter were carefully repaired and re-sown and a fertiliser was applied to help boost cover establishment and minimise

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competition for nitrogen with the vines. The cover was so poor prior to the summer that management to prevent potential competition with the vines for water or frost damage was not necessary.

It is possible that the exacerbated erosion may have been avoided if an alternative soil preparation method, such as direct drilling, had been used at the point of installation, or if strategy implementation had been left until the spring. Practicality dictates that the timing remains the same (section 3.2.4), and thus it is the method which will require further adjustment.

Rainfall intensities  $<6 \text{ mm h}^{-1}$  throughout July and August encouraged the sown vegetative cover to improve and develop a more even distribution. This was to pay dividends in the months that followed.

On the 3<sup>rd</sup> of September 2002, a period of dramatic storm activity hit the region. This lasted for several weeks, with event intensities as high as  $22.6 \text{ mm h}^{-1}$  (09/09/2002). Considerable quantities of soil were washed from the conventionally managed slopes causing rivers, field ditches and the main estate road to become inundated with sediment (Plates 3.2 and 3.3). A large scale clean-up operation using bulldozers and diggers was necessary. The situation was compounded by the ground remaining heavy and difficult to walk on for several weeks after the rains had stopped. The harvest had to be delayed and the farmer was faced with substantial accommodation costs for his migrant labour force. Subsequent storms in October rendered the land impassable by machinery until March 2003, thus preventing other viticultural management practices from taking place.

Throughout this storm period, the grassed inter-rows stayed intact and they could easily sustain pedestrian traffic immediately after rainfall. This simple demonstration, under extreme conditions, was enough for the farmer to consider employing the use of cover on other vulnerable parts of the estate.



*Plate 3.2*  
*On site effects of the September 2002 storms – La Romane, France*  
*(Ceri Llewellyn, Spring 2003)*



*Plate 3.3*

*Off site effects of the September 2002 storms – La Romane, France  
(Bruno Cailliau, September 2002)*

By spring of 2003, the cover was visibly improving soil stability and it appeared to be functioning at its maximum sediment trapping capacity (Plate 3.4). In April, temporary cover desiccation was necessary. Paraquat was applied in the form of Gramoxone Plus, at a rate of  $1.5 \text{ l ha}^{-1}$ . This application did not quite achieve the desired level of desiccation as dormancy was not induced. A recommendation was made by the Syngenta product trial technician to use  $2 \text{ l ha}^{-1}$  in future applications.

In the second week of April 2004, the vines were reaching a growth stage where water availability was of great importance and Gramoxone Plus was applied at  $2 \text{ l ha}^{-1}$  to the grass cover. When used at full strength ( $5 \text{ l ha}^{-1}$ ), the effects of this product are seen in less than twenty four hours. However, six days after application of this reduced dose rate desiccation had not occurred. A second application was therefore made at  $3 \text{ l ha}^{-1}$  and this proved to be successful.



*Plate 3.4*

*Grassed inter-rows at their maximum sediment trapping efficiency – La Romane, France  
(Ceri Llewellyn, Spring 2003)*

#### *3.3.3.2. Villarzel-Cabardes*

The timing of the strategy implementation at Villarzel-Cabardes was almost identical to that at La Romane and a similar problem with seed germination and cover establishment was encountered. The seed bed was prepared in an identical way but a different seed mixture was used: Viver PP60, a commercially available mixture of 60% smooth meadow grass, 30% creeping red fescue and 10% English rye grass, at  $4.5 \text{ g m}^{-2}$ . The seeded inter-rows were rolled and left for the autumn rains. However, the low soil temperatures encouraged much of the seed to remain dormant and the smooth soil surface began to seal.

In the spring of 2002, an attempt was made to encourage spreading of the existing cover and fragmentation of the crusted soil surface. A tractor mounted scarifier was drawn over each of the seeded inter-rows but it had little effect. By June of 2002, the surface vegetation cover had only reached 40 – 50%. Much of this cover was natural colonisation and had spread from the wasteland behind the field. Chemical desiccation was not deemed necessary.

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The first application of Gramoxone Plus was made in spring 2003 at  $2 \text{ l ha}^{-1}$ . This was sufficient to temporarily desiccate the sown cover but it killed much of the natural broad leaf vegetation, leaving bare patches of earth. In the autumn of 2003, the sown vegetation regenerated with much more vigour and spread to provide approximately 70% cover. The same dose rate was used in spring 2004 and no problems were encountered.

With the initial absence of torrential downpours, the shallower, shorter and more permeable slopes of this site presented only very subtle changes in visual appearance over time. Degradation was not obvious to the farmer and as a result of this he questioned the need for an alternative soil management practice under such field conditions. Surface channelling and reduced access to the land under conventional management after the heavier rainfall events (24/08/02 at  $3.6 \text{ mm h}^{-1}$ , 21/09/02 at  $18.8 \text{ mm h}^{-1}$  & 09/10/02 at  $10.4 \text{ mm h}^{-1}$ ) gradually illustrated the benefits of a vegetation cover to both the farmer and his neighbours.

The conventional soil cultivations were carried out at regular intervals throughout the spring and summer months each year. With just a few exceptions, due to the high soil moisture content, these cultivations were completed just prior to rainfall events.

In order to make a fair assessment of strategy effectiveness at conserving soil, in relation to conventional soil management practices (objective number 2, section 3.3), a certain degree of monitoring was necessary. A pragmatic approach was taken to produce the quantitative data required and the methods employed can be found in the following chapter.

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## **4. Quantitative demonstration of strategy effectiveness**

The fundamental premise for the work described here is that vegetative cover protects the soil from the erosive forces of rain splash and runoff. Roots add stability, improve structure and infiltration and generally contribute to an improvement in soil health. One may expect, therefore, that greater volumes of sediment and runoff would be obtained from a bare soil when compared to a vegetated one. However, it takes time for a cover to achieve such a level of protection. It may be three years or more before the vegetation is seen to have a significant effect (Anderson *et al*, 2001). Much will depend on the varieties used and the growing conditions experienced.

This chapter describes a monitoring programme which was set up to run in tandem with the implementation work discussed in Chapter 3. A unique feature of this monitoring programme is that it permits a direct and fair comparison of the treatments used at each site. This is only possible because data has been gathered right from the sowing of the cover, when two bare plots sat side by side. The monitoring programme is extremely important to the project, as it will contribute to the identification of strengths and weaknesses in the techniques used, permit improvement and present an honest demonstration to farmers and regulators. It may also help identify which parts of the strategy have the greater financial and environmental cost. This kind of information will be very useful to farmers and policy makers.

The following sections of this chapter describe the experimental design, the sampling procedures used and the results obtained.

### **4.1. Methods and materials**

In order to compare the effectiveness of each treatment in conserving soil and reducing runoff, an experimental programme was devised using the central inter-row in each of the treatment blocks. Restricted access to the field sites due to the sampling team being based in the UK, led to the design of a low maintenance collection system which could cope with multiple large scale runoff events.

A metal funnel was installed at the lower end of the inter-row. It had a detachable lid, to permit the removal of debris in the eventuality of a blockage, and a mesh placed over the mouth to prevent rabbits from entering the collection system and becoming trapped. The mouth of the funnel was mounted in a concrete apron and positioned such that it could not be undermined or bypassed and would catch all surface runoff leaving the plot. Material captured by the funnel was then channelled through a length of 200 mm diameter plastic pipe, positioned at a gradient of 1 in 10, to a series of Integrated Bulk Containers (plastic tanks), which had been adapted to serve as a collection system (Figure 4.1).

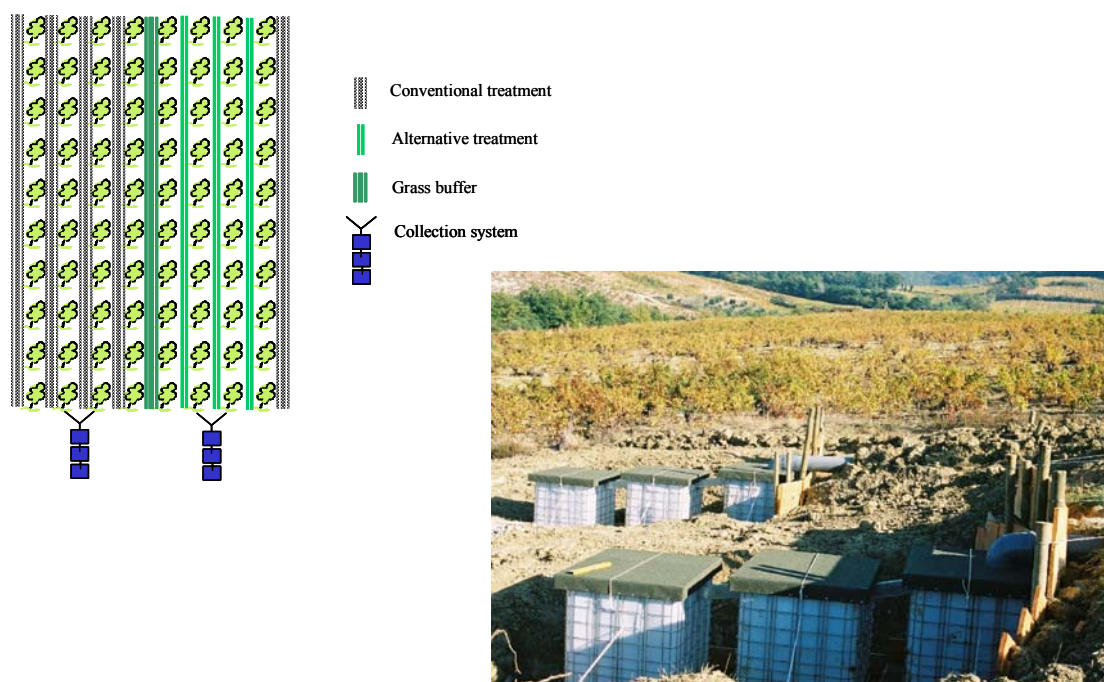


Figure 4.1

*Trial layout and tank collection system*

*(Ceri Llewellyn, Autumn 2001)*

All material funnelled down from the plot entered the first collection tank. Once the tank was full a known fraction of overspill was channelled into a second tank using a divisor. The second tank possessed the same divisor system as the first and led into the third tank in the system which remained closed. This permitted the calculation of total volumes of sediment and runoff leaving the plot.

A tank level sensor, made by attaching a float arm to a potentiometer, was installed in the first tank of each collection system. It was linked to the automatic weather station

positioned nearby. With the help of automated daily uploads of site data to the project website, field conditions were carefully monitored and rainfall events triggering runoff were identified. Sensitivity of the tank level sensors was such that they served only to show when runoff occurred and when the first tank in each collection system was full. Drawing detailed relationships between rainfall events and the runoff generated was not possible. It was necessary instead to consider the data on a cumulative basis.

Flumes and auto-samplers could have been used to monitor runoff and sediment generated from the inter-rows. However, low technology collection and sampling methods were considered to be more robust and better suited to this project. They also reduced the risk of data loss and frequency of field site visits and were relatively inexpensive to install and run. All monitoring equipment was installed at the site during October and November 2001.

Prior to the start of the erosion monitoring programme the main characteristics of each monitored plot were recorded. This was done for later use in calculating sediment and runoff losses. The measurements taken can be seen in Tables 4.1 and 4.2 below.

*Table 4.1*  
*Treatment plot characteristics for La Romane*  
*(As measured on the 17<sup>th</sup> January 2002)*

|                           | <b>Conventional treatment</b> | <b>Alternative treatment</b> |
|---------------------------|-------------------------------|------------------------------|
| Plot length               | 78.7 m                        | 79.3 m                       |
| Plot width (vine to vine) | 2.25 m                        | 2.25 m                       |
| Plot width (bund to bund) | 1.44 m                        | 1.35 m                       |
| Contribution zone         | 177.08 m <sup>2</sup>         | 178.43 m <sup>2</sup>        |

*Table 4.2*  
*Treatment plot characteristics for Villarzel-Cabardes*  
*(As measured on the 16<sup>th</sup> January 2002)*

|                           | <b>Conventional treatment</b> | <b>Alternative treatment</b> |
|---------------------------|-------------------------------|------------------------------|
| Plot length               | 40.3 m                        | 44.9 m                       |
| Plot width (vine to vine) | 2 m                           | 2 m                          |
| Plot width (bund to bund) | 1.25 m                        | 1.25 m                       |
| Contribution zone         | 80.6 m <sup>2</sup>           | 89.8 m <sup>2</sup>          |

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At three locations along the length of each monitored plot, the difference in height between the plot surface and the top of the adjacent bunds was recorded. This was done both at the beginning and at the end of the monitoring programme. To accommodate variations across the width of each plot, five measurements were taken at each location. The purpose of these height measurements was to enable the identification of any changes to plot surface profiles and discuss their significance in the context of the sediment and runoff results. For this reason, they can be found in the results section.

#### **4. 2. Sampling**

Sampling visits were made to a site once a tank had registered full, or if runoff had occurred and further rainfall was not expected for several weeks. The sampling regime used during the experimental programme was restricted to volumetric measurements of runoff and sediment, and textural composition of the sediment. Chemical analysis of sediment and runoff samples was also undertaken but these results are beyond the scope of this thesis.

Comprehensive recording of surface features, such as channel dimensions and type and percentage of cover in the monitored inter-rows, was initially carried out during sampling visits. This was later stopped on the grounds that it was too time consuming and involved walking on the plots when they were wet and fragile. Without knowledge of surface condition prior to a rainfall event the measurements obtained were also deemed to have limited value. Instead, brief notes were made and photographs taken of surface condition at the time of sampling. These were later used to supplement and interpret the sediment and runoff data collected.

Sampling was carried out manually and the collection tanks were sampled and emptied in sequence. Initially, the combined depth of water and sediment present in a tank was recorded. This information was later used to calculate a volume. Approximately 2 litres of the liquid fraction was then extracted by lowering the sample container from above. The remainder of the liquid fraction was then pumped off, revealing settled sediment in the bottom of the tank. The average depth of this wet sediment was also recorded for later use in volumetric calculations.

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Sediment was removed from the tank using a bucket of known (empty) weight, a metal dustpan and a car ice scraper. Each bucketful of sediment was weighed and sampled before disposing of the remainder. Collection of this information enabled a calculation of the total wet weight of sediment removed from the treatment plot.

One representative sediment sample was taken per tank by taking one sub-sample from each bucket of sediment removed. Thus, sample sizes varied between tanks and between visits.

Care was taken on entering the tanks to avoid the introduction of material which had accumulated outside. During extreme runoff events the deposition of sediment in the mouth of the funnels was occasionally seen. In these instances, a sample of the deposited sediment was taken for analysis and the remainder cleared away.

Samples were labelled in the field with the date, the name of the site, the treatment and the tank number. These samples were then taken to the local Syngenta technical centre, from where they were couriered to Syngenta's UK headquarters at Jealott's Hill near Bracknell. On arrival at Jealott's Hill, each sample was logged in a record book and given a unique identifier code (a common Syngenta practice) prior to being sent to NRM Laboratories, Bracknell, for analysis.

This monitoring programme lasted for three years, starting in November 2001 and terminating in December 2004. At its conclusion, a visual assessment of the effects of the two soil management activities on soil structure and condition was carried out at Villarzel-Cabardes. The techniques employed are those designed by Shepherd (2000) for use by farmers on arable and pastoral grazing land as shown in appendix 1. Although simple to carry out and requiring the most basic equipment, they are supported by a substantial amount of research. They can also demonstrate, in a matter of minutes, the positive and negative impacts of previous and current management on the soil.

Application of the Visual Soil Assessment to the Mediterranean vineyard situation was believed to be unique at the time it was carried out for this thesis. The author has since been working collaboratively with Shepherd on its adaptation and adoption in

this region. The results of the assessment (using the original format, at the end of the monitoring programme) can be found in section 4.3. Unfortunately, the high soil moisture content of the conventional treatment prevented the assessment from taking place at La Romane. The assessment works best when the soil is at its plastic limit or is sufficiently dry to prevent compaction. Components such as the ‘structure and consistence’ test cannot be carried out accurately if the moisture content is above the plastic limit as the soil mass is likely to deform instead of breaking up into structural units when dropped from a height of 1 m.

### 4. 3. Results

Cumulative totals from the monitoring programme (Table 4.3), show that the alternative treatment generated substantially less sediment than the conventional treatment at both sites. They also confirm that La Romane is much more susceptible to sediment and runoff losses than Villarzel-Cabardes.

*Table 4.3*  
*Cumulative total sediment & runoff losses (15/11/01 – 17/11/04)*

| Site               | Treatment    | Sediment (kg m <sup>-2</sup> ) | Runoff (l m <sup>-2</sup> ) |
|--------------------|--------------|--------------------------------|-----------------------------|
| La Romane          | Conventional | 16.53                          | 484.93                      |
|                    | Alternative  | 12.23                          | 509.57                      |
| Villarzel-Cabardes | Conventional | 4.33                           | 126.59                      |
|                    | Alternative  | 1.29                           | 163.26                      |

Presented in this way, the results say nothing about the different establishment phases encountered and their effects on soil or runoff losses, or the timescales involved and the interrelationships with rainfall and surface condition. All these pieces of information are necessary if weak points in the strategy are to be identified and rectified and if farmers and policy makers are to be encouraged to adopt the system.

It is necessary, therefore, to carry out a detailed critical analysis of the data, and this will start with an examination of treatment response and time. Subsequent analytical work will be developed from the findings and each section will follow from a hypothesis which is to be tested. Expectations will precede the actual results and discrepancies will be discussed. Each site will be dealt with separately and a summary of the key findings will be made at the end.

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#### 4.3.1. *La Romane*

Hypothesis 1: Treatment response is sensitive to time from the start of the monitoring programme.

Using the conventional treatment as a standard, no correlation can be expected between sediment or runoff losses and the length of time over which they were collected (the sampling period). This is because the length of each sampling period was determined by the nature of the rain which fell and by the surface condition of the plot at the time of rainfall (section 4.2). Neither of which remained constant. It is possible, however, that a relationship exists between sediment and runoff responses and time since the start of the monitoring programme. This is because, for the alternative treatment at least, the surface changed from one of bare soil in 2001 when the monitoring programme began, to one covered by a grass sward in 2004.

Based on the theory set down in section 2.2.2 and the experimental design (Chapters 3 & 4), it could be expected that, when starting with two bare plots; one roughly cultivated (conventional treatment) and one finely cultivated into a seed bed (alternative treatment), and the same environmental conditions, the sediment and runoff losses would be greater from the finely cultivated plot. This is because little energy is required for detachment, the soil is more readily available for transport and a finer surface has a lower roughness coefficient.

Once the cover has established on the alternative treatment and starts to provide surface protection, soil losses should reduce. A reduction in runoff losses would be expected to follow, once the roots have had a chance to improve soil structure and the cover has developed sufficiently to increase the roughness coefficient beyond that of the conventional treatment. As time progresses, losses from the alternative treatment should continue to decrease until the treatment reaches a point of maximum effectiveness.

Table 4.4 shows the dates at which sampling took place and the length of each sampling period in days. The method employed for determining sampling period length (section 4.2) gives a mean of 30.5 days with a standard deviation of 25.3. With such variability it has been decided that the best way of presenting the data for analysis is in time-series format; clearly marking the boundaries of each sampling

period and the total losses obtained from each treatment within each sampling period (Figures 4.2 & 4.3).

Looking at Figures 4.2 and 4.3, we can immediately see that two of our expectations have been satisfied;

- there is no correlation between the losses from the treatments and sampling period length, and
- for the first 4 sampling periods (15/11/01 – 22/05/02) the alternative treatment generated greater sediment losses than the conventional.

However, if we examine the runoff losses, the volumes generated from the first 3 sampling periods (15/11/01 – 08/05/02) are much lower in the alternative treatment than in the conventional – the opposite of what was expected. What might have caused this scenario? Rainfall and surface condition held the key.

*Table 4.4*  
*Sampling period (SP) dates and lengths*

| Sampling event N <sup>o</sup> | Sampling date | SP mid point | SP length (days) |
|-------------------------------|---------------|--------------|------------------|
|                               | 15/11/2001    |              |                  |
| 1                             | 27/02/2002    | 06/01/02     | 52               |
| 2                             | 20/03/2002    | 09/03/02     | 10.5             |
| 3                             | 08/05/2002    | 13/04/02     | 24.5             |
| 4                             | 22/05/2002    | 15/05/02     | 7                |
| 5                             | 10/06/2002    | 31/05/02     | 9.5              |
| 6                             | 12/09/2002    | 27/07/02     | 47               |
| 7                             | 18/10/2002    | 30/09/02     | 18               |
| 8                             | 14/11/2002    | 31/10/02     | 13.5             |
| 9                             | 19/12/2002    | 01/12/02     | 17.5             |
| 10                            | 13/02/2003    | 16/01/03     | 28               |
| 11                            | 23/04/2003    | 19/03/03     | 34.5             |
| 12                            | 09/12/2003    | 16/08/03     | 115              |
| 13                            | 27/01/2004    | 02/01/04     | 24.5             |
| 14                            | 04/03/2004    | 14/02/04     | 18.5             |
| 15                            | 26/05/2004    | 14/04/04     | 41.5             |
| 16                            | 25/08/2004    | 10/07/04     | 45.5             |
| 17                            | 27/10/2004    | 25/09/04     | 31.5             |
| 18                            | 17/11/2004    | 06/11/04     | 10.5             |

Denotes an extreme set of rainfall events resulting in an incomplete data set

Denotes missing laboratory data

Cover was sown in October 2001

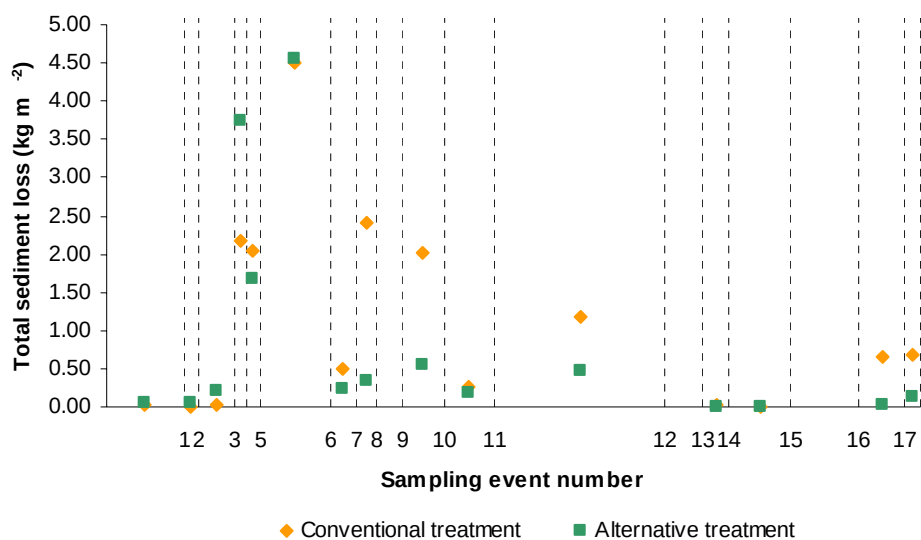


Figure 4.2  
Sediment losses over the life of the project.

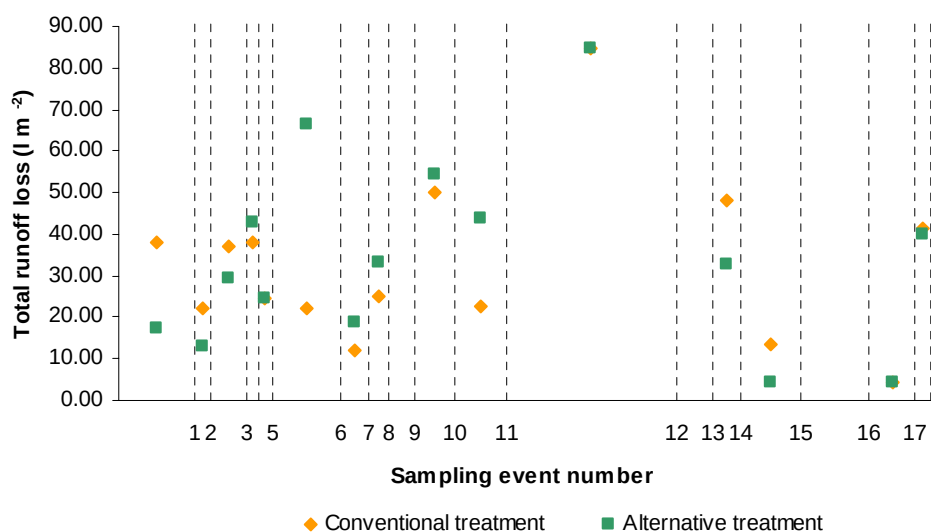


Figure 4.3  
Runoff losses over the life of the project

Much of the sediment derived from the alternative treatment plot during the first three sampling periods was the result of low intensity rainfall events lasting 6 hours or more. The majority of the sediment was comprised of aggregates which were 2 – 3 mm in diameter and remained stable when submerged in water or when compressed. They were formed by the mechanical preparation of the seedbed and on examination of the work of Poulenard *et al* (2001), it is believed that exposure to a long period of

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air drying caused high levels of shrinkage to occur which reduced porosity of the aggregates and caused them to become hydrophobic.

A seedbed formed of such hydrophobic aggregates would have resulted in a higher infiltration rate than a rough but sealed surface akin to that of the conventional treatment. This is because the stability of the aggregates on wetting would have ensured that the transmission pathways for water between the aggregates remained open. The higher surface tension of the uncultivated layer below would have presented a significant barrier to infiltration and thus, the seedbed would have been prone to saturation. Once saturated, little energy would have been required to detach or transport the aggregates from the monitored plot.

A single rainfall event of 55 mm, lasting 8 hours, was the cause of the high sediment and runoff responses for both treatments in the 4<sup>th</sup> sampling period.

At some stage within the 5<sup>th</sup> sampling period (22/05/02 – 10/06/02) and approximately 6 months into the monitoring programme, the cover of the alternative treatment started to offer some protection to the soil, thereby reducing sediment loss to less than that of the conventional treatment. This trend continued for the remainder of the monitoring programme. However the margin between the two treatment responses fluctuated considerably.

These fluctuations can be partially attributed to treatment sensitivity to rainfall intensity and duration. Infrequent cultivation of the conventional treatment plot, due to low soil load bearing capacity and farmer forgetfulness when cultivating other parts of the vineyard, is also believed to be a cause. Absence of cultivation resulted in ‘frost heave’ (the forcing apart of soil aggregates as the water within them expands as it freezes) being the only mechanism by which new soil material was brought to the surface. Rock fragments, which had once been part of the soil matrix, limited the amount of soil available for detachment by forming a protective stone cover (Plate 4.1). This finding is in agreement with the work of Ollesch & Vacca (2002) which explored the temporal variability of sediment losses from 18 uncultivated erosion plots in Sardinia, Italy.

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An estimation of percentage stone within the soil matrix at the start of the trial was not made, due to there being no stone fragments visible at the surface or when carrying out the profile assessment. Thus, a calculation of the increase in stoniness by volume with time has not been possible.



*Plate 4.1*

*Formation of a protective stone cover on the conventional treatment plot – La Romane, France  
(Ceri Llewellyn, February 2003)*

On examination of the data in Figures 4.2 and 4.3, the results from the 6<sup>th</sup> sampling period (10/06/02 – 12/09/02) do not appear to meet the trend mentioned above. However, it has been noted in Table 4.4 that this is an incomplete data set caused by a series of extreme rainfall events. From the 24<sup>th</sup> – 27<sup>th</sup> of August 2002, there were several rainfall events in close succession. These events would have been sufficient to bring the cultivated layer of soil under both treatments up to saturation. Shortly after this, between the 2<sup>nd</sup> and 9<sup>th</sup> of September, there were six major storm events, two of which reached intensities in excess of 20 mm h<sup>-1</sup>. The results were dramatic.

The movement of sediment on the conventionally tilled plot had been so great during the first of the major storms that the funnel had been completely overwhelmed. This we know from photographs taken during a brief visit immediately after the storm (Plate 4.2). Sediment and runoff from subsequent storms was forced to bypass the collection system as a result, whilst the collection system of the alternative treatment continued to function as normal.

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Despite the loss of a significant amount of runoff and sediment data from the conventional plot, a simple calculation based on the material collected tells us that soil loss from that first major storm alone equated to more than 45 t ha<sup>-1</sup>. Soil loss from the alternatively treated plot must have been significantly less, as it generated this amount for the whole sampling period.



*Plate 4.2*

*Blockage of the funnel on the conventionally managed inter-row, versus the clear funnel on the inter-row under alternative management – La Romane, France*

*(Bruno Cailliau, 4<sup>th</sup> of September 2002)*

Between the sampling events of 09/12/03 (number 12) and 04/03/04 (number 14), runoff losses from the alternative treatment became less than those from the conventional treatment. This indicates that the grass cover of the alternative treatment had reached its final establishment phase. However, the possibility of infiltration impedance caused by the stone cover on the conventional treatment plot should not be ruled out.

The results imply that the response from the alternative treatment is sensitive to time. It took approximately 6 months from the date of sowing for the cover to start reducing soil loss, and  $\geq 2$  years for it to influence infiltration and runoff. Unfortunately, the response from the conventional treatment has been confused by inconsistent management.

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Hypothesis 2: Rainfall is the dominant factor influencing treatment response.

From field observations, common sense and variations in the sediment and runoff losses discussed above, treatment response appears to be sensitive to rainfall. Statistical analysis of the field data is necessary to determine if rainfall is the dominant factor influencing treatment response or if there is at least one more factor with greater influence on the results.

The presence of a relationship between total rainfall and total sediment loss per sampling period is not anticipated. This is because a value for total rainfall gives no indication of the intensity or kinetic energy with which the rain fell. Intensity and kinetic energy can vary considerably for periods of rainfall which generate the same total volume, thus, they have the potential to generate very different amounts of sediment.

Identifying a statistical relationship between rainfall intensity and sediment losses might have been possible if sampling had taken place after each individual rainfall event. For reasons explained in sections 4.1 and 4.2, this was not the case and thus, an alternative approach was necessary.

Morgan (2005) states that the severity of erosion is directly related to the energy available for soil detachment. By taking the rainfall data for each sampling period and calculating the total kinetic energy for each hour, using the equations below, the results can be summed to give total kinetic energy (TKE) in  $\text{J m}^{-2}$  for each sampling period. TKE for each sampling period can then be plotted against losses to see if a relationship exists.

$$KE = 11.87 + (8.73(\log_{10}I))$$

$$TKE = KE \times \text{rainfall}$$

Where:

$$KE = \text{J m}^{-2} \text{mm}^{-1}$$

$$I = \text{intensity (mm h}^{-1}\text{)}$$

$$TKE = \text{J m}^{-2}$$

$$\text{Rainfall} = \text{mm}$$

(from Morgan, 2005)

Theory would suggest that the higher the total kinetic energy of a sampling period, the greater the erosive potential. Thus, for a bare soil a positive, first order polynomial relationship could be expected between TKE and sediment losses.

For a partially established cover (one which has started to reduce soil loss but not yet had an influence on infiltration and runoff), the TKE at which sediment losses start to occur is likely to be higher than that for bare soil. The slope of the line is also expected to be less steep because the cover and the roots are offering some protection and stability.

From the time at which cover begins to reduce runoff losses by improving soil infiltration capacity, it is considered to be fully established. At this stage, sediment losses are not anticipated, regardless of increases in TKE, as the cover should be providing total protection from the forces of rain splash and runoff.

It has already been noted that the surface conditions of both treatment plots were undergoing change throughout the life of the monitoring programme. It is not surprising, therefore, that no significant relationships are visible when all the data for each treatment are considered together (Figure 4.4).

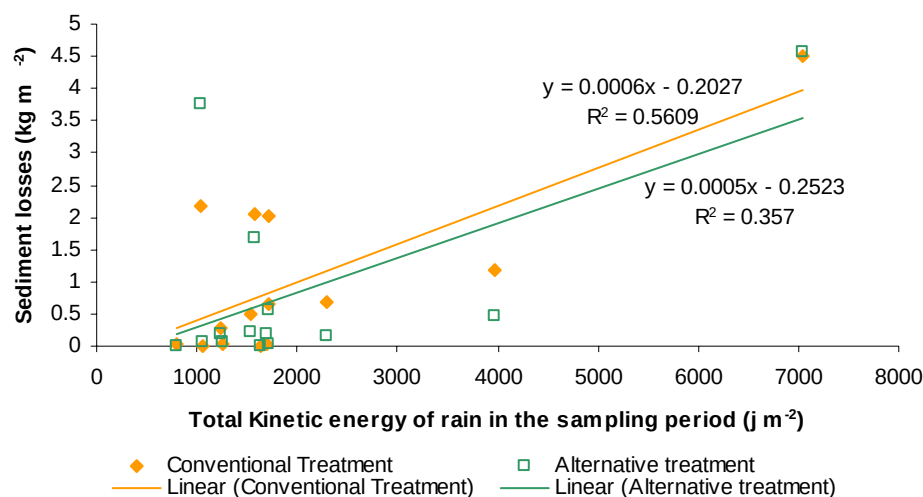


Figure 4.4  
TKE and sediment losses throughout the life of the project

Little more can be done with the sediment data from the conventionally managed plot to test hypothesis 2. However, timescales for the different establishment phases of the alternative treatment plot were identified whilst testing hypothesis 1, and relationships may be present if the data is considered in those stages.

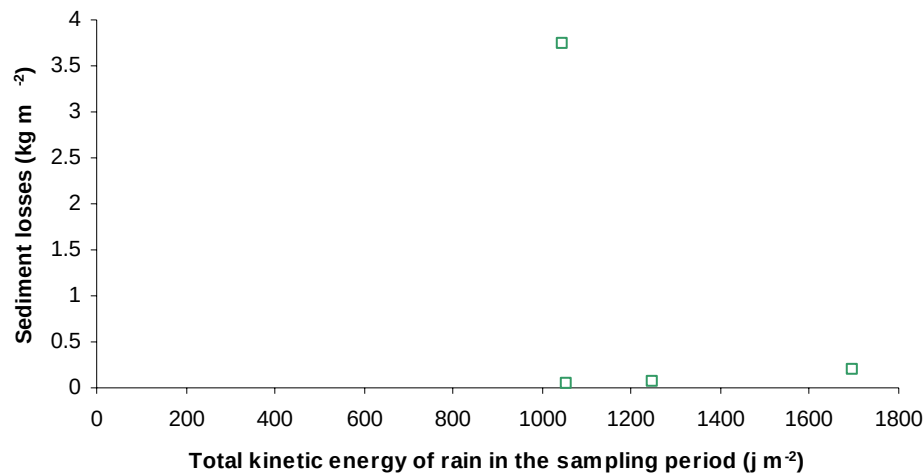


Figure 4.5

*Sediment / TKE relationship for establishment phase 1:  
Bare soil – cover providing protection (15/11/01 – 22/05/02)*

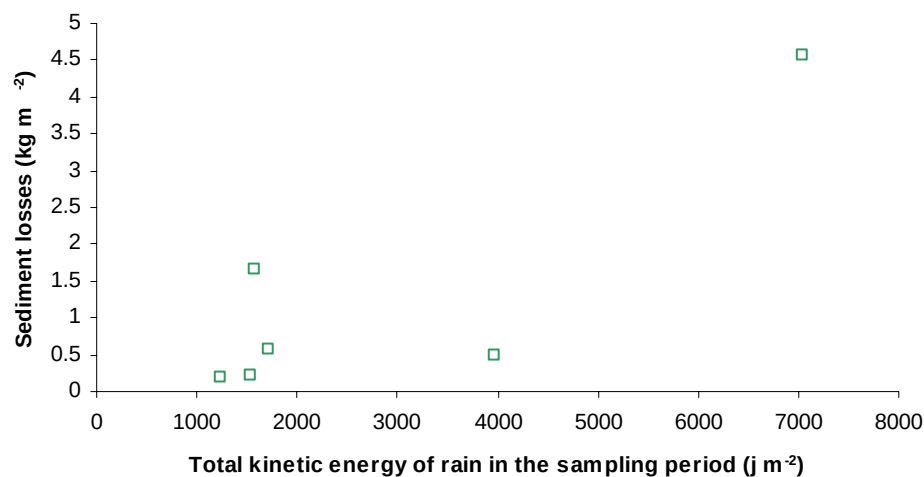


Figure 4.6

*Sediment / TKE relationship for establishment phase 2:  
Cover providing protection – cover improving infiltration (23/05/02 – 09/12/03)*

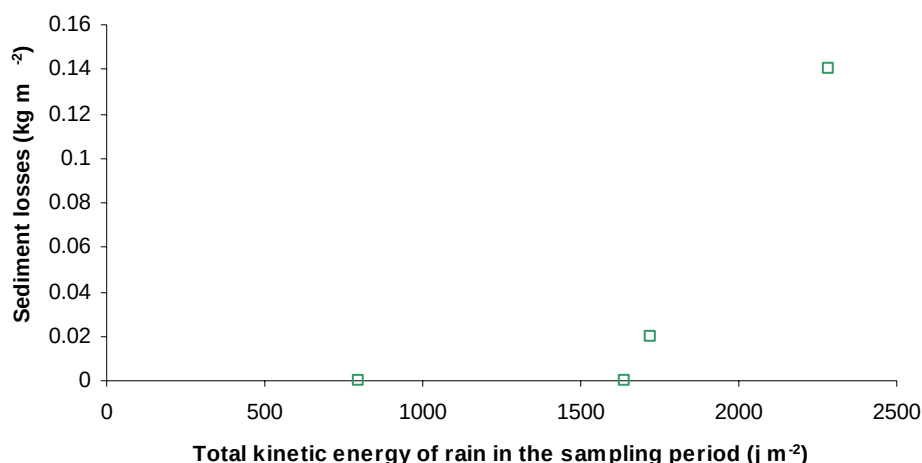


Figure 4.7

*Sediment / TKE relationship for establishment phase 3:*

*Cover improving infiltration – end of monitoring programme (28/01/04 – 17/11/04)*

With reference to Figures 4.5 – 4.7, it can be seen that there are too few data points to enable a meaningful analysis and that there is a large amount of scatter. A possible explanation for the level of scatter is that TKE is usually calculated on an individual storm basis, it is not normally used to link data from several storms together. Some sampling periods in the monitoring programme contained only one heavy storm, and others contained several medium sized storms or several small ones, which could result in the same TKE value. On examination of the rainfall data, it is believed that this is the cause of the scatter in Figures 4.5 and 4.6.

From left to right, the data shown in Figure 4.7 are arranged in date order. Despite continued improvement in the vegetation cover present, it is apparent that the sediment losses were steadily increasing with TKE. The results would suggest that either the grass was only providing partial protection or sediment was entering the plot from outside the stabilised zone; either from the unprotected vine row or from an adjacent plot.

Inspection of the plot confirmed that sediment was indeed coming from the vine row (Plate 4.3) and this was supported by the change in the height of the bund as seen in Table 4.5. In some instances, preferential flow paths had developed at the point where

the bare soil met the stabilised soil. This highlights the need for vine row stabilisation to avoid aggravated soil loss around the roots of the vines.



*Plate 4.3*

*Grass partially covered with soil from the vine row – La Romane, France  
(Ceri Llewellyn, Winter 2004)*

The data in Table 4.5 also show a general lowering of the bund relative to the inter-row on the conventional treatment plot. This is thought to be due to the reduced cultivation and the presence of stones which largely protected the inter-row from incurring greater erosion losses.

*Table 4.5*

*Plot profile measurements taken prior to the start of and on completion of the monitoring programme*

|                             | <b>Conventional</b> |            | <b>Alternative</b> |            |
|-----------------------------|---------------------|------------|--------------------|------------|
|                             | <b>Start</b>        | <b>End</b> | <b>Start</b>       | <b>End</b> |
| Height of natural bund (mm) |                     |            |                    |            |
| Top of plot                 | 160                 | 100        | 120                | 50         |
| Middle of plot              | 160                 | 100        | 190                | 100        |
| Bottom of plot              | 130                 | 140        | 170                | 110        |

Starting profiles were different between treatments, for reasons beyond the author's control. The data was collected to identify changes in treatment plot profiles and assess their significance in the context of the sediment and runoff losses from the individual treatments.

The energy of rain falling on a plot has little influence on the volume of runoff which will be generated. Instead, it is the moisture content of the soil prior to rainfall, the surface roughness and the total amount of rain to fall, which are mostly responsible (Morgan, 2005).

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Although financial constraints prohibited direct measurement of soil moisture, and runoff was not measured after every rainfall event, there is potential to explore the relationships between rainfall and runoff with the data available. For example, antecedent rainfall can be used as a surrogate for soil moisture.

For each individual sampling period it is possible to identify rainfall events which had the potential to generate runoff. As rainfall was logged at 30 minute intervals, it has been decided that an 'event' should be defined as a period of rainfall which contained breaks no longer than 30 minutes. 'Events' therefore varied in duration between 30 minutes and several hours and breaks between 'events' lasted a minimum of 1 hour.

In their evaluation of temporal effects on sediment and runoff losses from abandoned grazing land in Sardinia, Ollesch & Vacca (2002) used rainfall events  $\geq 3$  mm in their erosivity calculations. This value had been derived from some unpublished work by Ollesch which identified the threshold value of  $\geq 3$  mm of rainfall as being capable of generating runoff on plot experiments with similar soil types (between 73 & 39% sand, 39 & 5% silt and 22 & 13% clay). At La Romane the soil is 4% sand, 35% silt and 61% clay. It can be assumed that permeability would therefore be significantly lower by comparison with Ollesch's work, and that runoff would occur in response to smaller rainfall events. On this basis, it has been decided that rainfall events  $\geq 2$  mm should be considered as having the potential to generate runoff.

Rain which fell in the 12 hours prior to the start of an event has been summed to provide a surrogate for soil moisture. The event rainfall and the antecedent rainfall have then been combined to give an overall value of 'significant' rainfall in mm. Where several rainfall events occur within one sampling period, the values have been summed to produce an overall value for the significant rainfall pertaining to that sampling period. Figure 4.8 shows the relationship between runoff losses and the rain deemed to be significant in each sampling period.

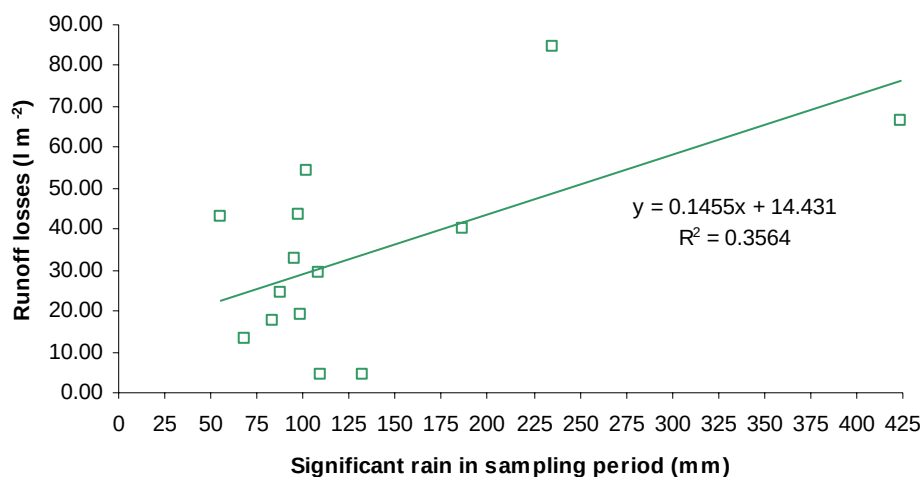


Figure 4.8

*Rainfall / runoff loss relationship for the alternative treatment*

This method has its pitfalls. The use of antecedent rainfall as a substitute for antecedent soil moisture did not allow for the soil moisture loss via evaporation, the soil moisture deficit (the reduction in soil water due to transpiration exceeding rainfall), or the maximum water holding capacity of the soil, and it is clear that not all rainfall events  $\geq 2$  mm would have had the potential to generate runoff. Unfortunately, Ollesch and Vacca (2002) do not discuss these limitations but they are believed to have resulted in the overestimation of significant rainfall in this model. Where significant events were close together, the same period of rainfall may have been counted several times. This would have also caused an overestimation. With reference to Figure 4.8, it is believed that the failure to accommodate these factors in the model was the cause of the poor correlation.

Due to the continuous change in the degree of cover and its growth state (dormant or active), it is not possible to calculate with accuracy the evaporative losses from the plot and the soil moisture deficit for each sampling period. Thus, it would be difficult to include the missing factors in the model without introducing a significant degree of error. Had soil moisture monitoring been in place, the calculation of evaporative losses and soil moisture deficit would not be necessary.

From the available data, it has not been possible to determine whether rainfall kinetic energy is the dominant factor influencing sediment loss. Soil moisture content prior to rainfall and volume of rainfall are believed to be the dominant factors influencing runoff at this site, however, corroboration of this theory has not been possible.

#### 4.3.2. Villarzel – Cabardes

Hypothesis 1: Treatment response is sensitive to time from the start of the monitoring programme.

In adopting the same analytical approach as used for La Romane, Table 4.6 shows that the sampling was less frequent at Villarzel – Cabardes. The 73 day mean sampling period length was more than twice that of La Romane, with a standard deviation of 32.7. Fewer big rainfall events occurred in this region during the monitoring programme and this combined with the smaller contribution zones and shallower slope angles meant that the collection tanks at Villarzel – Cabardes took longer to fill. In having fewer sampling points, the resolution of the data is reduced.

Table 4.6  
Sampling period (SP) dates and lengths

| Sampling event N <sup>o</sup> | Sampling date | SP mid point | SP length (days) |
|-------------------------------|---------------|--------------|------------------|
|                               | 01/12/2001    |              |                  |
| 1                             | 12/04/2002    | 05/02/02     | 132              |
| 2                             | 26/06/2002    | 19/05/02     | 75               |
| 3                             | 14/08/2002    | 20/07/02     | 49               |
| 4                             | 16/10/2002    | 14/09/02     | 63               |
| 5                             | 16/12/2002    | 15/11/02     | 61               |
| 6                             | 09/04/2003    | 11/02/03     | 114              |
| 7                             | 24/06/2003    | 17/05/03     | 76               |
| 8                             | 01/09/2003    | 28/07/03     | 69               |
| 9                             | 19/12/2003    | 25/10/03     | 109              |
| 10                            | 03/03/2004    | 25/01/04     | 75               |
| 11                            | 07/04/2004    | 20/03/04     | 35               |
| 12                            | 06/05/2004    | 21/04/04     | 29               |
| 13                            | 24/08/2004    | 30/06/04     | 110              |
| 14                            | 23/09/2004    | 08/09/04     | 30               |

Denotes missing laboratory data

Cover was sown in October 2001

With reference to Figure 4.9, the results of the first two sampling periods for which data are available confirm expectations that the fine seed bed of the alternative treatment aggravated sediment loss. The stability of the roughly cultivated surface of the conventional treatment helped to keep sediment and runoff losses low (Figure 4.10).

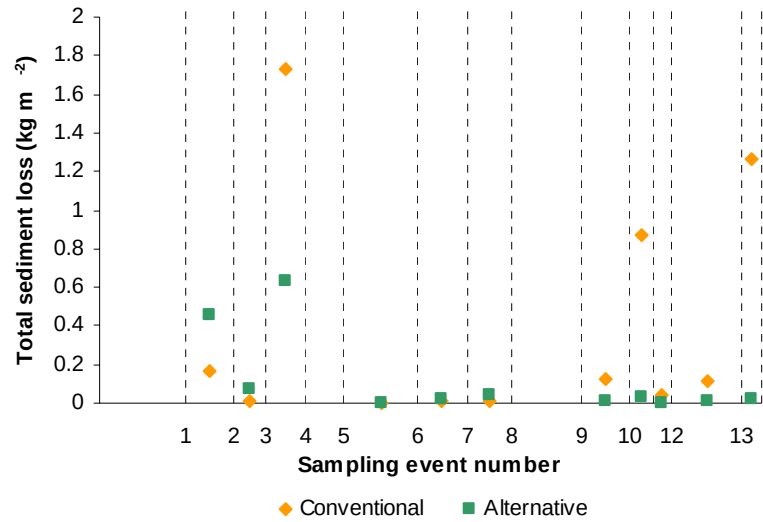


Figure 4.9  
*Sediment losses over the life of the project*

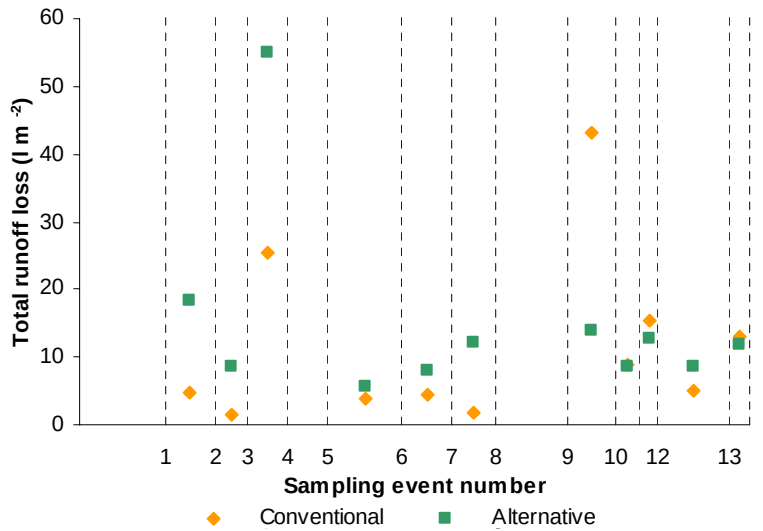


Figure 4.10  
*Runoff losses over the life of the project*

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In sampling period 4, sediment losses were substantially reduced under the alternative treatment but runoff losses were much higher. Observations made in the field showed that the vegetation cover was up to 50% at this point but that the surface was still very smooth. A substantial channel had formed down the centre of the conventional plot but the surface was still much rougher, and thus, had greater potential to reduce surface flow.

The time at which the alternative treatment provided a protective effect against soil loss is unclear. Initially, it is seen to occur in the period 14/08/02 – 16/10/02 (event numbers 3 to 4); almost a year after sowing, but then very little sediment was generated from either treatment during the period 09/04/03 – 01/09/03 (event numbers 6 to 8). During the period 19/12/03 – 03/03/04 (event numbers 9 to 10), more than two years after sowing, sediment losses increased once more from the conventional treatment and the protective effect of the alternative treatment became clearly visible.

As discussed in section 3.3.3.2, establishing a grass cover at this site was difficult. Despite having been sown, much of the cover which formed initially was due to natural colonisation (Plate 4.4).



*Plate 4.4*

*Large proportion of natural cover present – Villarzel-Cabardes, France  
(Michel Speyer, April 2003)*

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Use of Gramoxone in spring 2003 to desiccate the sown cover resulted in the death of the natural cover, leaving bare patches for much of 2003 (Plate 4.5). Re-initiation of the protective phase coincided with the cover-improving infiltration phase, as indicated by the reduction in runoff losses.



*Plate 4.5*

*Bare patches of earth caused by selectivity of herbicide & resulting in concentrated flow paths*

*Villazzel-Cabardes, France*

*(Michel Speyer, June 2003)*

The data analysis implies that the response of the alternative treatment at Villazzel – Cabardes is sensitive to time from the start of the monitoring programme. However, the trends present are not as clearly defined as those at La Romane. This is thought to be due to the problems with cover establishment and management and the regular but seasonal cultivation of the conventional treatment plot which were described in Chapter 3.

Hypothesis 2: Rainfall is the dominant factor influencing treatment response.

Theory would suggest that the higher the TKE for a sampling period, the greater the erosive potential on unprotected soils. However, the data from the conventional treatment presented in Figure 4.11 do not corroborate this. The limited resolution of the data (being per sampling period rather than per rainfall event) prevents identification of the reason for this but it is possible that the regular cultivations prior to rainfall, during the spring and summer months, had a significant influence. The three points at which sediment losses are seen to be greatest were during October

2002, April 2004 and September 2004. All of these are outside the main cultivation period, thus the soil surface would have undergone some structural deterioration and levelling by rainfall and overland flow, making it more vulnerable to erosion.

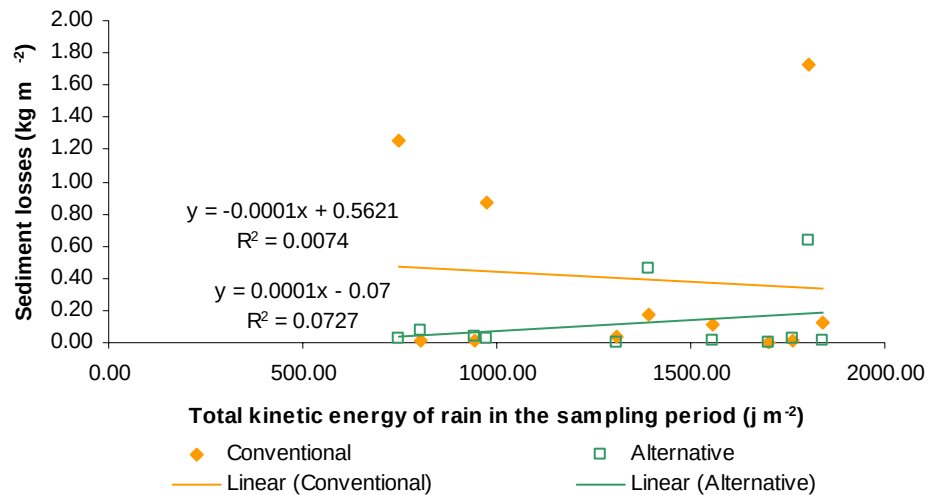


Figure 4.11

*TKE and sediment losses throughout the life of the project*

To examine the relationship between TKE and the sediment loss from the alternative treatment, the data set has been split up into its establishment phases (Figures 4.12 and 4.13). Establishment phase 1 has been omitted from this analysis as there are only two data points.

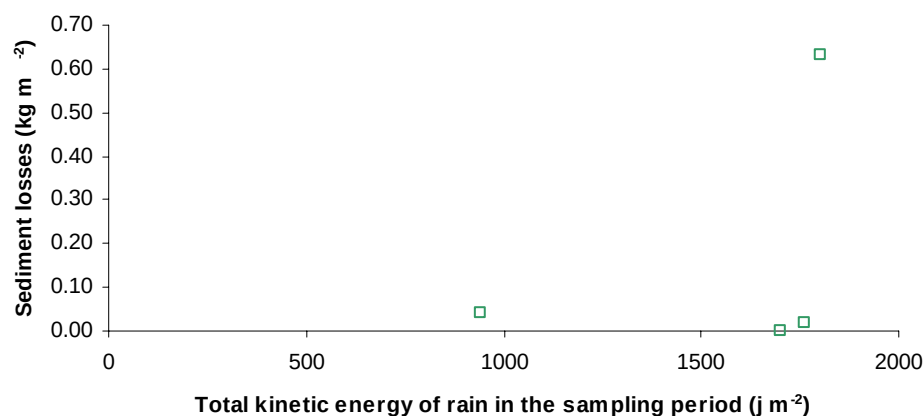


Figure 4.12

*Sediment / TKE relationship for establishment phase 2:*

*Cover providing protection – cover improving infiltration (16/10/02 – 01/09/03)*

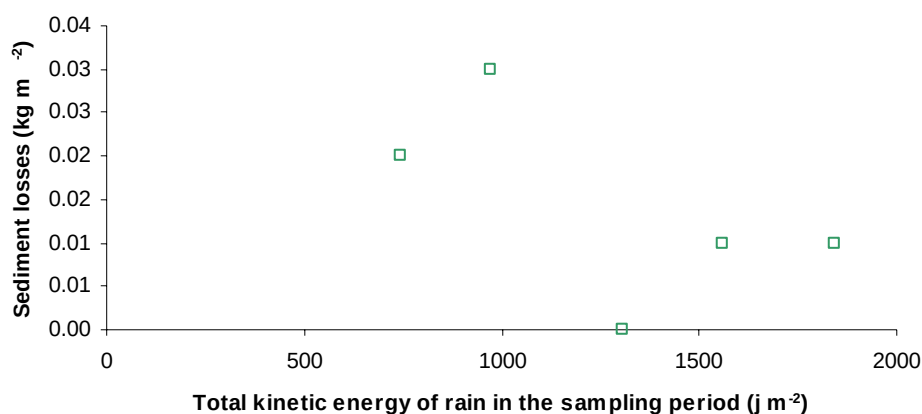


Figure 4.13

*Sediment / TKE relationship for establishment phase 3:*

*Cover improving infiltration – end of monitoring programme (03/03/04 – 23/09/04)*

As with the data from La Romane, there are too few points to carry out a meaningful analysis and this is a function of the weather experienced over the life of the monitoring period and the sampling procedure used. Fluctuations in percentage cover combined with the use of multiple storm TKE data are thought to have had a significant influence on the level of scatter present.

Table 4.7 shows changes in the height of the bunds relative to the monitored plot surfaces since the start of the monitoring programme. Under the conventional soil management, there has been an increase in the height difference between the two surfaces at the top of the plot. Relatively little has changed at the mid-slope and there has been an increase towards the bottom, where the slope is at its steepest (Table 3.1).

Table 4.7

*Plot profile measurements taken prior to the start of and on completion of the monitoring programme*

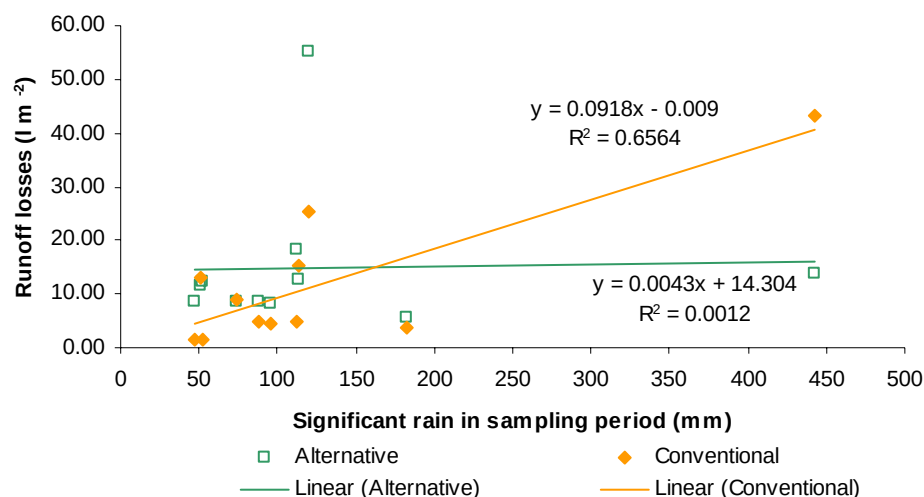
|                             | Conventional |          | Alternative |         |
|-----------------------------|--------------|----------|-------------|---------|
|                             | Start        | End      | Start       | End     |
| Height of natural bund (mm) |              |          |             |         |
| Top of plot                 | 25 – 90      | 60 – 100 | 80          | 40 – 80 |
| Middle of plot              | 70 – 120     | 70 – 100 | 130         | 95      |
| Bottom of plot              | 140 – 190    | 20       | 200         | 20      |

Starting profiles were different between treatments, for reasons beyond the author's control. The data was collected to identify changes in treatment plot profiles and assess their significance in the context of the sediment and runoff losses from the individual treatments.

Under the alternative treatment, the height difference between the top of the bund and the plot surface has reduced at all three locations. Although there is no photographic evidence, it is extremely likely that this lowering has been caused by the vegetative protection and stabilisation of the inter-row whilst the vine row has been left unprotected. It highlights the need for soil protection measures to be implemented across the whole vineyard and not just in the inter-row.

Given the data available, it is not possible to conclude whether rainfall or surface roughness is the more dominant factor influencing sediment loss at this site. To try and establish whether rainfall and antecedent soil moisture are the dominant factors influencing runoff, the significant rain in each sampling period has been plotted against the runoff obtained (Figure 4.14) using the method described in section 4.3.1 for La Romane.

The data presented in Figure 4.14 show that, for both treatments, there is a poor correlation between significant rainfall, i.e. that which is thought capable of causing runoff, and the measured runoff losses.



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inappropriate. With the data available, it cannot be proven that rainfall is the dominant factor influencing runoff losses at this site.

The effects of the two soil management practices on the soil's physical condition were examined at the end of the monitoring period using the Visual Soil Assessment method (appendix 1). The results of this assessment are expressed in Plate 4.6 and Table 4.8. They show that in the short life of the trial the presence of the vegetation cover and the associated microbial activity have started to increase its porosity and its organic matter content, which is reflected in the change in colour. These findings concur with the increase in soil structural stability indicated by the reduction in sediment losses from the alternative treatment in the field monitoring programme (Figure 4.9).



*Plate 4.6*

*Pictures of soil structure from samples taken from the conventional (left) & alternative (right) treatments at the end of the monitoring programme – Villarzel-Cabardes, France  
(Graham Shepherd, 2005)*

*Table 4.8*  
*Results of the soil assessment carried out at the end of the monitoring programme*

| Visual indicators of soil quality           | Visual Score (VS) Conventional | Weighting factor | VS ranking Conventional | Visual score (VS) Alternative | Weighting factor | VS ranking Alternative |
|---------------------------------------------|--------------------------------|------------------|-------------------------|-------------------------------|------------------|------------------------|
| Soil structure & consistence                | 1.5                            | X 3              | 4.5                     | 1.5                           | X 3              | 4.5                    |
| Soil porosity                               | 1                              | X 3              | 3                       | 1.5                           | X 3              | 4.5                    |
| Soil colour                                 | 0.5                            | X 2              | 3                       | 1                             | X 2              | 2                      |
| Number & colour of soil mottles             | 1.5                            | X 2              | 3                       | 2                             | X 2              | 4                      |
| Surface ponding                             | 1.5                            | X 2              | 3                       | 2                             | X 2              | 4                      |
| Earthworm counts                            | 0                              | X 2              | 0                       | 0                             | X 2              | 0                      |
| Tillage pan                                 | 2                              | X 2              | 4                       | 2                             | X 2              | 4                      |
| Degree of clod development                  | 0                              | X 1              | 0                       | 2                             | X 1              | 2                      |
| Soil depth                                  | 2                              | X 2              | 4                       | 2                             | X 2              | 4                      |
| <b>Soil Quality Index (sum of rankings)</b> |                                |                  | <b>22.5</b>             |                               |                  | <b>29</b>              |
| <b>Soil Quality Assessment</b>              | <b>Soil Quality Index</b>      |                  | <b>Conventional</b>     |                               |                  | <b>Alternative</b>     |
| Poor                                        | <10                            |                  |                         |                               |                  |                        |
| Moderate                                    | 10 – 25                        |                  | <b>X</b>                |                               |                  |                        |
| Good                                        | >25                            |                  |                         |                               |                  | <b>X</b>               |

For sampling and scoring criteria, please refer to appendix 1

A reduction in the number of soil mottles and amount of surface ponding are further indications of improved soil structure and soil health. Reduced ponding and mottling are a result of improved soil drainage and aeration and thus a reduction of anaerobic activity and the production of toxins in the soil. Overall, the presence of the cover has changed the quality of the soil from moderate to good. The difference between the two treatments is expected to increase with time.

The Visual Soil Assessment has proven to be a very useful tool when applied to the Mediterranean vineyard situation. This is because the visual indicators used have come from traditional soil surveying practice. Soil crusting is a typical feature of Mediterranean vineyards under traditional management and has a significant influence on soil permeability. Soil erodibility is also a function of soil structure and health. If the assessment is to be tailored more specifically to the Mediterranean vineyard situation, the author suggests that the degree of soil crusting and the degree of soil erosion by water are included as visual indicators.

In the original Visual Soil Assessment, plant indicators such as: crop emergence, height at maturity, size and development of the crop root system, crop yield, weed

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infestation and surface ponding (for arable), and: pasture composition, pasture growth, area of bare ground, drought stress, surface ponding and stock carrying capacity (for pasture), were also considered. This information was then compared with the findings from the soil assessment to get a more detailed understanding of the impacts of soil management on productivity. Given that the factors which influence vine productivity are very different to those which influence the productivity of arable and pastoral grazing land, a plant assessment was not made in this study. Work is needed to identify vine indicators which would be most suitable for inclusion in a plant assessment.

#### ***4.4. Summary of key findings from the monitoring programme***

- On the alternative treatment plot, the seedbed preparation method combined with a long period of dry weather was found to make the soil hydrophobic at La Romane. The method also aggravated soil loss at both sites. Thus an alternative approach needs to be sought.
- Total sediment losses were reduced by the presence of a cover at both sites within the 3 year monitoring period and soil physical condition was found to have visibly improved at Villarzel-Cabardès within the same time frame.
- The resolution and therefore the value of the data could be improved if they were collected on an event basis rather than over a variable number of events.
- At La Romane, the sensitivity of the alternative treatment to time since the start of the monitoring programme is clearly visible. It took approximately 6 months for the cover to establish sufficiently to stabilise and protect the soil and  $\geq 2$  years to improve infiltration capacity and reduce runoff. On the alternative treatment at Villarzel-Cabardès, the establishment phases are not as well defined. This is thought to be due to the problems with cover establishment and the more timely cultivations on the conventional plot.
- At both sites, the stabilisation of the inter-rows using vegetation has emphasised the erosion of the vine rows. Practical methods of soil stabilisation and protection need to be found for these vulnerable zones.
- Antecedent rainfall was found to be a poor substitute for antecedent soil moisture because it doesn't take account of evaporative and transpiration losses or the maximum water holding capacity of the soil.

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- There is insufficient data to determine whether rainfall is the dominant factor influencing treatment response.
  - The Visual Soil Assessment proved to be a useful tool for gathering information on soil structural condition and fertility in this study. Identification of suitable plant productivity indicators, which are related to soil condition, is necessary if the assessment is to be tailored properly to the Mediterranean vineyard environment. A suggestion that soil crusting and erosion be included as soil indicators has also been made.

The cover establishment problems at both sites made it impossible to rigorously test and develop chemical management techniques in the field. However, it was identified that Paraquat could be successfully used to induce a state of dormancy. In 2004, funding was secured to extend the research by a further two years. This provided the opportunity to assess the indirect impacts of several herbicide treatments on a soil's potential to erode, and to find an optimum product and dose rate for cover management. The initial experimental work and its key findings are presented in Chapter 5.

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## ***5. Identification of a suitable desiccant for cover management***

Whilst Paraquat's ability to induce dormancy in a sown grass cover was demonstrated in the field (sections 3.3.3.1 and 3.3.3.2), the dose rates used may not have been the optimum. There remains the need to examine dose effect on plant performance for soil protection and stabilization. There is also the need to consider alternative products, in order that an optimum cover management solution can be found.

In Spring 2005, a unique experimental programme was initiated to address these needs. Preliminary laboratory studies were set up to test the hypothesis that herbicide product and dose rate influence a soil's potential to erode, due to their effect on plant physiology. Plant and soil physical characteristics relating to soil protection, permeability and structure were used to assess soil erosion potential under a variety of herbicide treatments. The work took place under controlled environmental conditions at Jealott's Hill International Research Station, Bracknell, and the National Soil Resources Institute, Silsoe. The experimental design and key findings are described in the following sections.

### ***5.1. Experimental design***

#### ***5.1.1. Pot preparation and cover establishment***

On the 15/02/05, thirty five plant pots were each numbered and packed with 3237 g of a uniform sandy loam, 2 mm screened and air dried soil, to a bulk density of  $1.2 \text{ g cm}^{-3}$ . Each pot had a surface area of  $226.98 \text{ cm}^2$  and was sown with *Lolium Multiflorum* at a rate of  $5000 \text{ seeds m}^{-2}$ .

The pots were placed in a glasshouse where the minimum day and night time temperatures were set at  $20^\circ$  and  $15^\circ$  respectively, and day length was set to 16.8 h. Watering took place in the morning, three times per week, on Monday, Wednesday and Friday. This was done from the base by adding 0.05 l to the individual trays in which the pots were standing.

Emergence took place on the 19 and 20/02/05. From the time of emergence, plant development was closely monitored and cutting of the cover to a height of 5 cm was carried out on two occasions (02/03/05 and 07/03/05) to encourage tillering and

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improve cover development. This procedure simulated the mechanical mowing which would take place under field conditions. Five of the pots were allocated for destructive sampling and root examination. This was to help with the timing of treatment application. It was important to ensure that the treatments were applied before the plants became pot bound. Pot binding is an artificial situation which may cause the plants to exhibit stress responses which could be confused with responses to the treatment.

#### *5.1.2. Treatment application*

Ten cover management treatments were chosen by Syngenta for the study:

Paraquat at 0.75, 1.5, 3 and 5 l ha<sup>-1</sup>, in the form of Gramoxone, and a water treated control, each replicated three times.

Glyphosate at 0.75, 1.5, 3 and 4 l ha<sup>-1</sup>, in the form of Touchdown, and a water treated control, each replicated 3 times.

Glyphosate was selected as the second herbicide for a number of reasons:

- It is still permitted for use in French vineyards.
- It has a different mode of action to Paraquat.
- Knowledge of the product led to the belief that it may be possible to induce dormancy in cover by manipulating the dose rate.

The active ingredient was mixed with deionised water to produce an application volume of 400 l ha<sup>-1</sup>, as used in the field. These treatments were allocated to the numbered pots using a completely randomised design.

On the 23/03/05, the pots were transferred to a spray laboratory where all the herbicide applications were made using a track sprayer. Visual assessment showed the plant cover to be at approximately 50%. After treatment application the pots were returned to the glass house and allocated random positions, where they remained for the next 21 days.

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Visual assessments of the percentage herbicide effect on the cover and the percentage of cover present were made 1, 7, 14 and 21 days after treatment application - an assessment interval commonly used by Syngenta in their chemical trials. These assessments were made so that the rate and extent of treatment action on the cover could be compared.

### *5.1.3. Plant and soil physical analysis*

For each pot the following measurements were taken:

- Surface cover biomass, 21 days after application – by harvesting and oven drying at 102°C for 18 hours,
- Permeability at saturation – using a falling head permeameter,
- Shear strength of the root / soil matrix at saturation – using a pocket tor vane (type CL100) in 3 positions on the soil surface at a depth of 5 mm,
- Organic matter – using loss on ignition (BS 1377 – 3:1990),
- Dry root density – after oven drying at 102°C for 18 hours,

It took approximately 3 weeks to complete the latter 4 measurements. The pots were worked on in randomised batches of 6, due to equipment availability. Whilst pots awaited analysis, they were kept in the dark at 4°C to prevent further growth.

## **5.2. Results & discussion**

In order to test the hypothesis stated at the beginning of this chapter, the first and most important stage in the data analysis was to identify if product and/or dose rate affected any of the parameters measured. If no treatment effects could be found then the study would conclude that there was insufficient evidence to support the hypothesis. Given that the two products used in the trial have different modes of action; Glyphosate being systemic, Paraquat being contact, it was anticipated that product effects would be present. An increase in effect with dose rate was also anticipated.

The data were processed using a general analysis of variance. This revealed that there were no significant product or dose effects on soil permeability, organic matter or shear strength. However, all the plant parameters measured were affected (Statistical detail is presented in appendix 3).

It is known that the death and decomposition of plant roots creates drainage channels in the soil, loosens the soil/root matrix, thereby reducing its shear strength, and contributes organic matter to the soil – as does the decomposition of above-ground plant material. It would therefore be reasonable to anticipate a treatment effect in the plant data to be reflected in the soil data. The presence of a treatment effect on the plants but absence of an effect on the soil in this study indicates that it takes more than 21 days for the changes in the plants to influence soil physical properties.

With this information, focus was turned to identifying the product or dose effects on the plants.

### 5.2.1. Dry root density

The data presented in Figure 5.1 show that the root densities of the water treated controls were significantly greater than those from the pots treated with herbicide. However, no significant difference was found between the two products.

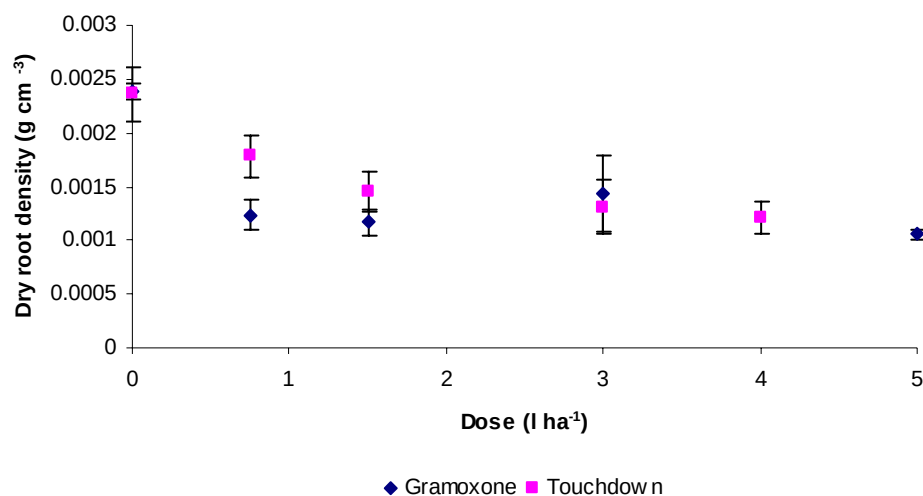


Figure 5.1

*Mean & standard error of treatment effects on dry root density, 21 days after application*

When carrying out the destructive sampling of the pots, it was noted that those treated with Touchdown at 3 and 4 l ha<sup>-1</sup> all contained wet soil and a blackened root mass which emitted an anaerobic odour. This indicates that the plants' capacity to take up water had ceased by 21 days. Combined with total desiccation of the surface cover, the evidence suggests that the plants had been killed rather than put into a state of artificial dormancy. This finding suggests that a 3 or 4 l ha<sup>-1</sup> dose of Touchdown is

unsuitable for use as a cover management tool in the chosen application, as it is important that the cover is capable of regenerating naturally later in the year. The root masses for all pots treated with Gramoxone were still white after the same time period, indicating that the plants were still alive.

We can hypothesise from this that if the post application period had been extended, the dead roots of the high dose Touchdown treated pots would have decomposed and a significant reduction in dry root density in the Touchdown treated pots would be seen. It is also expected that this effect would reduce the shear strength of the soil/root matrix and increase soil permeability and organic matter content.

### 5.2.2. Surface biomass

Figure 5.2 illustrates some significant differences in surface biomass between products and dose rates.

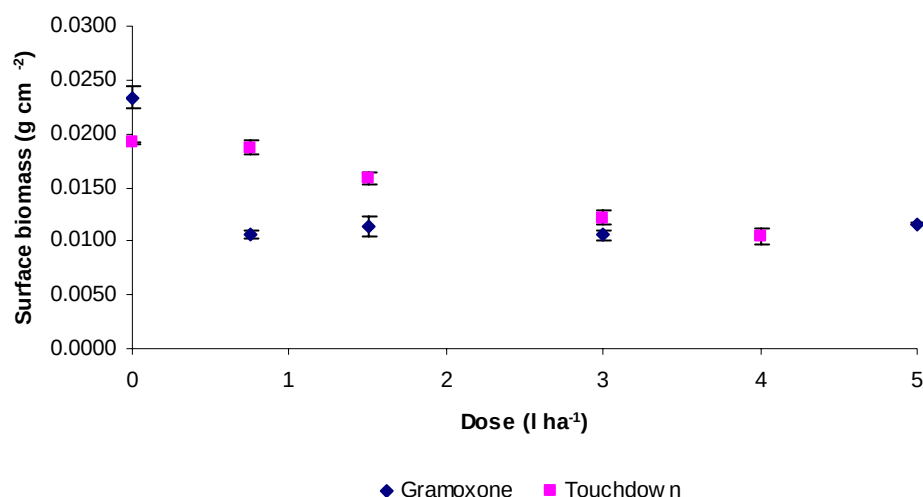


Figure 5.2

*Mean & standard error of treatment effects on surface biomass, 21 days after application*

With the exception of the water treated controls, no significant differences were found in surface biomass on the Gramoxone treated pots, regardless of dose. For Touchdown however, dose rates greater than or equal to 1.5 l ha<sup>-1</sup> showed a significant reduction in surface biomass with increase in dose.

At the dose rates of 0.75, 1.5 and 3 l ha<sup>-1</sup>, the surface biomass measured on the Touchdown treated pots was significantly higher than that on the Gramoxone treated pots. It could be assumed from this that a greater level of soil protection is achieved using Touchdown in a dose range of 0.75 – 3 l ha<sup>-1</sup>, than by using Gramoxone. To test this hypothesis, it is important to examine the effects of each treatment on the percentage of cover which has been desiccated and on the overall percentage cover in each pot.

### 5.2.3. Desiccation and cover

With reference to Figures 5.3 and 5.4, it can be seen that a higher and faster level of desiccation can be achieved using Gramoxone. The slower rate and lower level of desiccation expressed in the 0.75 and 1.5 l ha<sup>-1</sup> Touchdown treated pots would have permitted the plants to continue growing for a longer period of time. This, in turn, helps to explain why there was more surface biomass present from the Touchdown treated pots, as previously shown in Figure 5.2.

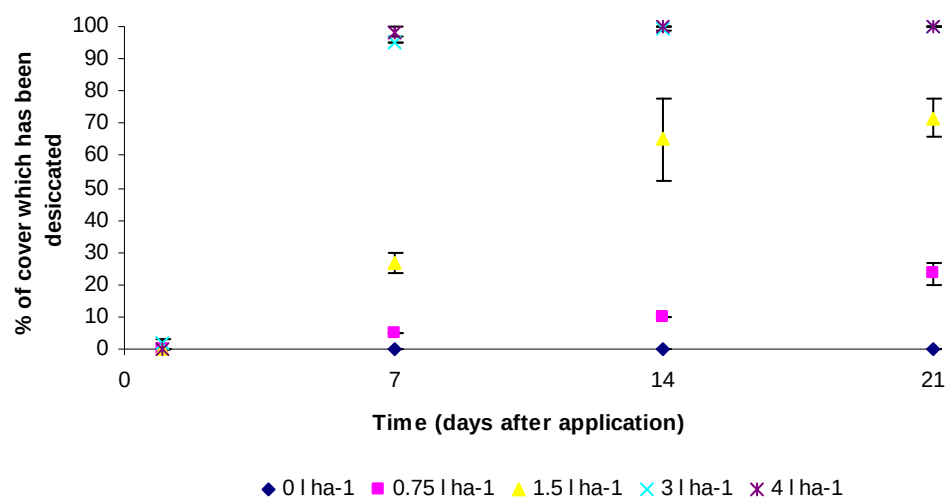


Figure 5.3

Mean & standard error of % desiccation with time after applications with Touchdown

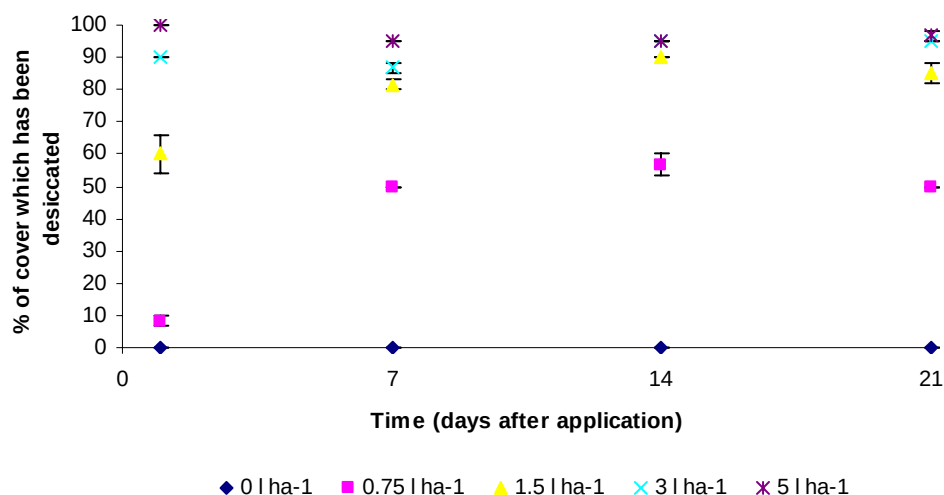


Figure 5.4

*Mean & standard error of % desiccation with time after applications with Gramoxone*

For the Touchdown treated pots, there was a significant difference in the level of cover desiccation between 0, 0.75 and 1.5 l ha<sup>-1</sup> dose rates with time and no re-growth was experienced. Pots treated with the 0.75 l ha<sup>-1</sup> dose were still experiencing a steady increase in desiccation on the final assessment date, 21 days after application. Thus, its maximum effect on the plants and the time taken to achieve it remains unknown. For cover management in a vineyard situation, where the onset of water stress can be very rapid, such a time delay in suppressing cover growth may not be acceptable.

For the Gramoxone treated pots, maximum desiccation was achieved using 3 l ha<sup>-1</sup> and no re-growth was experienced, yet examination of their roots showed the plants were still alive. Pots treated with 1.5 l ha<sup>-1</sup> achieved the same level of desiccation as those treated with 3 l ha<sup>-1</sup> by day 14. However, some re-growth was experienced between day 14 and 21, resulting in a significant decrease in the percentage cover shown to be desiccated by the treatment. In terms of desiccation, the ideal dose of Gramoxone for cover management in these environmental conditions appears to be >1.5 l ha<sup>-1</sup> but ≤ 3 l ha<sup>-1</sup>.

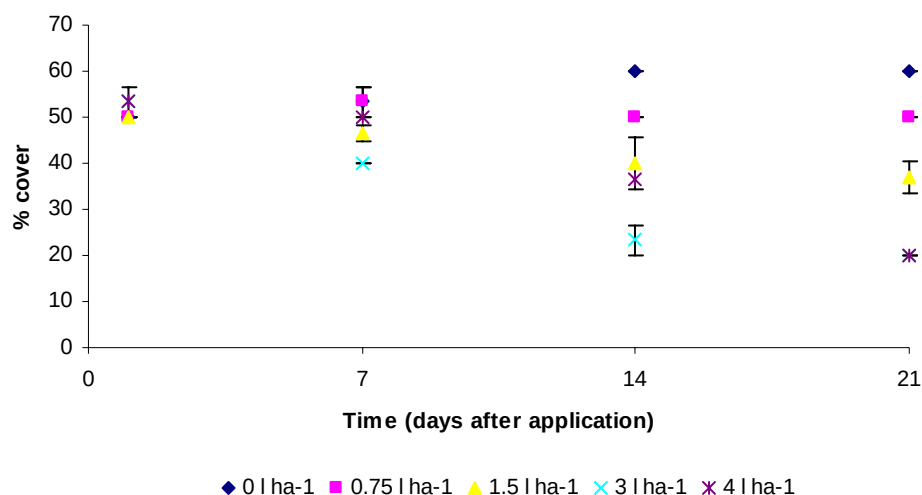


Figure 5.5

Mean & standard error of % cover over time after application with Touchdown

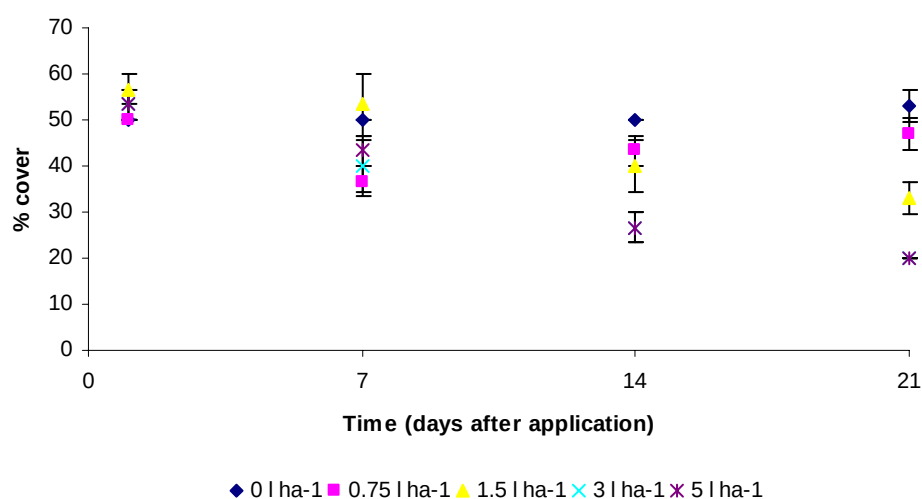


Figure 5.6

Mean & standard error of % cover over time after application with Gramoxone

Examination of treatment effects on the percentage cover with time (Figures 5.5 and 5.6), reveal that pots sprayed with 0.75 l ha<sup>-1</sup> of Touchdown experience no significant changes, whilst those sprayed with 1.5 l ha<sup>-1</sup> show a progressive decrease as expected. 0.75 l ha<sup>-1</sup> applications of Gramoxone caused a decrease in cover over the first seven days, followed by an increase in cover, as the plants recovered. At 1.5 and 3 l ha<sup>-1</sup>, only decreases were measured.

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Now that treatment influence on the level of desiccation and percentage cover have been explored temporally, the next aim is to identify if there is a suitable product and dose range which meets the cover management requirements of the wider research project. Changes to French environmental legislation, made in response to the Water Framework Directive, are anticipated to permit only 1 application of an individual herbicide per year (Julien, 2005 - Pers com). Thus an important project objective must be to identify the product and dose range which achieves the greatest level of desiccation without killing the plant or reducing the soil cover so much that it becomes highly vulnerable to erosion.

It may be argued that two different herbicides could be used to manage the cover in a single year, provided that they are permitted by the regulatory authorities. However, from an environmental and economic perspective, the ability to achieve the optimum effect with only one application of herbicide has to remain a key objective.

Analysis of the data so far has shown that, with the exception of one treatment (0.75 l ha<sup>-1</sup> of Touchdown), maximum treatment effect on the above-ground portion of the plants has been reached by 21 days. It would be prudent therefore to examine data from this time frame when trying to identify the optimum product and dose rate.

The effect of each treatment on % cover present and % cover desiccated 21 days after application are presented in Figure 5.7. As expected, there is a negative relationship between the % cover present and the % cover which has been desiccated by herbicide.

Ideally, the optimum product and dose should be located in the upper right quartile of Figure 5.7, however none of the treatments used fit into this area. It has already been identified that applications of Touchdown at 3 and 4 l ha<sup>-1</sup> kill the plants, and that a 3 l ha<sup>-1</sup> application of Gramoxone causes the same level of desiccation as 5 l ha<sup>-1</sup>, thus, focus needs to be turned to the performance of the lower doses tested.

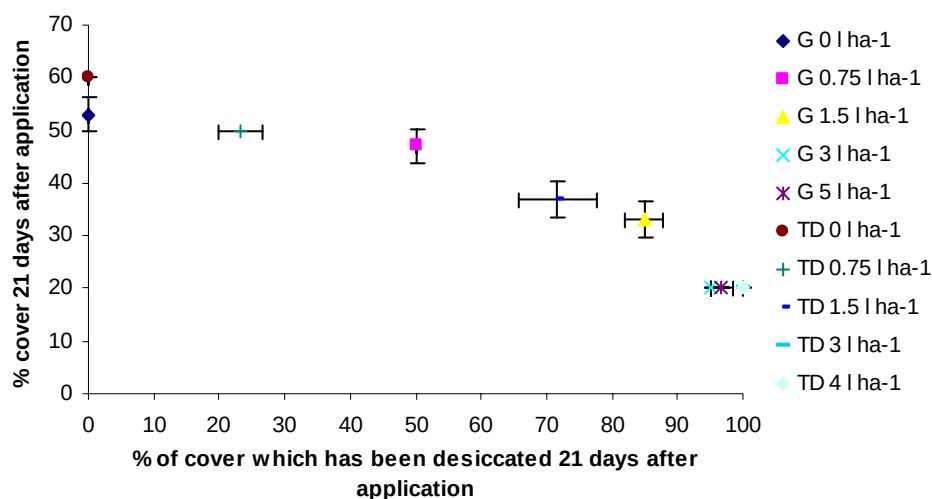


Figure 5.7

*Treatment effects on the desiccation / cover relationship, 21 days after application with standard error*

At both 0.75 and 1.5 l ha<sup>-1</sup>, Gramoxone caused a significantly higher level of desiccation than Touchdown, with an insignificant reduction in % cover. This implies that Gramoxone is the more suitable of the two products for use as a cover management tool in a soil conservation programme.

### 5.3. Summary of key findings from the experiments

There is sufficient evidence to accept the hypothesis that herbicide product and dose rate influence a soil's potential to erode, due to the effect they have on plant physiology.

- None of the treatments applied were found to influence soil structural properties within the 21 day post-application time frame.
- Herbicide application significantly reduced dry root density compared to the water treated controls but differences between products and doses were not present at 21 days post application.
- Touchdown applications at 3 and 4 l ha<sup>-1</sup> killed the plants, thus rendering them unsuitable dose rates for the chosen cover management application.
- None of the Gramoxone applications killed the plants, however, the 3 and 5 l ha<sup>-1</sup> doses achieved the same level of desiccation, thus, rendering the use of 5 l ha<sup>-1</sup> unnecessary.
- Pots treated with the lower doses of Touchdown exhibited higher surface biomass levels than those treated with Gramoxone, and this is attributed to a longer period of

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productive growth prior to onset of desiccation and a lower percentage of cover being desiccated.

- From the studies carried out, Gramoxone has the greatest potential as a cover management tool within a soil conservation programme, at dose rates between 1.5 and 3 l ha<sup>-1</sup>.
- Applications of Touchdown at 0.75 and 1.5 l ha<sup>-1</sup> result in a higher % cover remaining to protect the soil surface from erosion. However, their rate of action and degree of desiccation are inappropriate for the proposed cover management task. Dose rates between 1.5 and 3 l ha<sup>-1</sup> need to be tested for their suitability.

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## ***6. Synthesis and conclusions***

The main purpose of this research programme was to contribute to the development of a soil conservation strategy, suitable for use in Mediterranean viticulture, and to demonstrate that strategy's effectiveness at conserving soil. This has largely been achieved through a review of literature, application of project team expertise, and field and laboratory testing.

The research has confirmed that cover crops are not an instant solution to the soil erosion problem. In the field demonstration, described in Chapters 3 and 4, it took a minimum of six months from the time of sowing for the cover to start to reduce soil losses. This time frame was not only determined by the species used but, more importantly, by the environmental conditions experienced. Irrespective of this time delay, the author believes that permanent cover remains a more practical alternative to the re-engineering of the vineyard.

Care must be taken in selecting suitable grass species in order to minimise risk of competition for water and nutrients and to ensure the development of a dense sward. Management of the cover should involve a combination of mechanical and chemical techniques. Figure 6.1 illustrates how this soil management strategy fits in with the weather conditions for the Mediterranean region, the key vine growth stages and the viticulture calendar.

The greatest economic costs associated with this strategy arise at the installation phase; when investments will need to be made for equipment and seed. Management costs will be significantly less than those presently incurred for keeping the soil bare. In the long term, production costs will also reduce, as fewer vines are lost to erosion and accessibility to the land is improved. This will enable viticulture procedures to be carried out at the optimum time. In the field study presented in this thesis, improved accessibility to the land was achieved less than one year after sowing.

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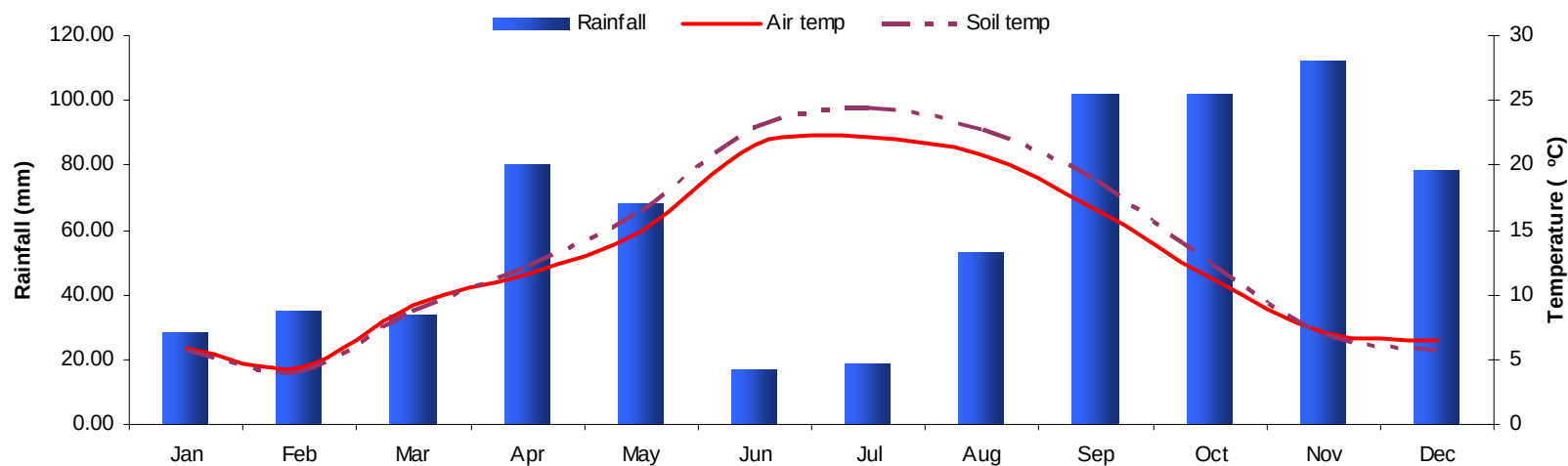
The greatest environmental cost of this soil management approach is between installation and cover establishment. Using the current installation methods, soil losses can be significantly aggravated and thus a more suitable installation method needs to be found. Once a cover has become established, substantial environmental benefits can be seen; the soil is stabilised, allowing physical improvements in its health to take place, and sedimentation of water courses and roads is prevented.

Measurable improvements in soil structure and fertility were noted in this study only three and a half years after the cover was sown, using the Visual Soil Assessment for arable and pastoral grazing land. Suggestions have been made to adapt the assessment so that more information can be gained from its use in a vineyard situation.

Protection and stabilisation of the inter-row has emphasised soil erosion losses from the vine row. Work needs to be done to convince farmers that this land also needs to be protected. Potential methods need to be identified and tested for their suitability in an established plantation.

Due to resource limitations, quantitative data which describe the treatment effect on the vines are not available. As farmer avoidance of vegetative covers has historically been due to fears of water stress, it would be prudent to examine the influence of the two treatments on soil water availability at critical times during the vine growth cycle. Information on the movement of water through the soil profile, in response to a rainfall event, would also be beneficial.

Field demonstrations and laboratory experiments have shown that herbicides can be used to induce a state of dormancy in a sown grass cover. The laboratory experiments have also shown that herbicide product and dose rate can indirectly influence a soil's potential to erode. More research is necessary in order to identify the most suitable product and dose rate for cover management with respect to erosion control.



|                                             |  |         |                                                 |                           |                                                              |          |                                          |                                    |  |
|---------------------------------------------|--|---------|-------------------------------------------------|---------------------------|--------------------------------------------------------------|----------|------------------------------------------|------------------------------------|--|
| Vine growth stage                           |  |         |                                                 | Veg growth starts         | Anthesis                                                     | Veraison |                                          | Senescence & abscission            |  |
| Vine management                             |  | Pruning |                                                 | Pest & disease management |                                                              |          | Harvest                                  |                                    |  |
| Soil management strategy – year 1           |  |         |                                                 |                           |                                                              |          |                                          | Seedbed prep, sowing and emergence |  |
| Soil management strategy – subsequent years |  |         | Mowing, scarification & 1 herbicide application |                           | Permanent grass cover in state of herbicide induced dormancy |          | Dormancy broken by change in the weather |                                    |  |

Figure 6.1

*A synthesis of the soil management strategy with the Mediterranean climate and key stages in the viticulture calendar*

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## **7. Recommendations**

### **7.1. Improvements to the experimental approach**

Given fewer financial constraints and greater availability of land for trials the main monitoring programme could be extended. Sampling could take place after every runoff event and more sensitive tank sensors could be installed. This would permit the production of hydrographs and the calculation of sediment losses for individual storm events, thereby allowing treatment performance to be more accurately compared under different types of rainfall.

Although primarily set up as a demonstration, the scientific rigour of the field trials could be improved by greater replication. An increase in the number of sites and the number of plots per site is needed to allow investigations into the interactions between slope angle, soil type and treatment performance. It is plausible that there will be field conditions under which this soil management technique will not work, and it would be useful to identify the boundaries of its functionality.

To get a better indication of treatment performance and sustainability over time, it is recommended that the monitoring programme should continue for at least another 5 years. To supplement this, a ‘visual soil assessment’ should be carried out each year as a rapid and simple means of monitoring the change in soil physical condition. Assessments should be carried out to identify if there is a need for artificial inputs or whether increases in organic matter content have been sufficient to improve the cation exchange capacity of the soil and thus the availability of the nutrients within it.

Nutrient losses associated with sediment and runoff were not discussed in this thesis. The time delays between sampling and analysis were thought to have permitted the alteration of sample chemical composition, particularly nitrate and ammonium content. Reliable data would have allowed loss comparisons to be made between treatments. This would have had significant value both from an environmental and an economic perspective. It is recommended that in future soil management trials of this nature, arrangements are made for samples to be taken to a local laboratory with the stipulation that they are kept under specific storage conditions and processed within a fixed time frame.

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## **7.2. Supplementary investigations**

An assessment of alternative cover establishment methods is necessary to identify one which is better suited to the field conditions. At La Romane, there is a need to prevent seedbed saturation and sealing. To achieve this, either the amount of water entering the soil needs to be reduced or drainage to the layers below needs to be improved. One possible option for reducing the amount of water entering the soil is to install a perforated plastic film over the seedbed (Blackburn, 2003). This would also help to increase soil temperature and speed up germination, although, installation costs would limit its use to the most vulnerable parts of the vineyard.

Poor drainage to depth was caused by a significant change in surface tension between the cultivated and uncultivated soil layers (section 4.3.1). Thus the drainage problem can be resolved by reducing this surface tension difference. Mechanically fracturing the soil below the seedbed, to reduce the surface tension in this layer, and use of a coarse seedbed are possible options.

To progress with the identification of the most suitable product and dose rate for cover management, a further set of controlled laboratory trials is necessary. To get the best value from the experimental work described in chapter 5, it is recommended that the same environmental conditions are used and the effects of 0 - 3 l ha<sup>-1</sup> dose rates for both herbicides are assessed at greater resolution. The pots should be left for more than 21 days after chemical application and before destructive sampling. This would help with the identification of plant recovery rates and possibly give a better indication of treatment effect on soil structural properties. Once laboratory testing has been completed, field verification at the plot scale would be necessary.

Once implemented at the plot scale adjacent to conventional soil management, comparative studies of treatment effect on soil water availability and soil water movement should be carried out. The findings of this work are anticipated to have a significant influence on farmer willingness to implement the cover management techniques. Thus it is essential that the studies are as comprehensive as possible. Continuous monitoring of volumetric moisture content at regular intervals throughout the vine root zone will be necessary. For calculation of available water, the volumetric moisture contents at which field capacity (the point at which free drainage ceases) and

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permanent wilting point (the point at which suction exerted by the plant roots is insufficient to extract water) occur at each of these intervals will also need to be known.

If the anticipated effect of improved soil water availability under a chemically managed cover can be proved and demonstrated in the inter-row, farmers may accept its use throughout the whole vineyard. If in principle, the use of vegetation cover in the vine row was accepted, there is still the practical issue of its installation on a ridge of crusted bare soil. Lack of cultivation should mean that beneath the surface crust the physical structure of the soil is reasonably well developed. However, a means of applying the seed to the ridge and breaking down the surface crust is necessary. A similar scenario is encountered in the civil engineering industry, with particular reference to motorway embankments. Here, a method known as hydro-seeding is commonly used, where seed is applied in a mulch and nutrient slurry. The slurry is designed to stick to the soil surface and to provide the seed with the basic requirements for germination and establishment. It is sprayed over the target surface from a pressurised vessel. Thus it is easy to apply to areas which are beyond the reach of tractor-drawn implements. At present there is no reason why attempts should not be made to apply this method to the vine ridge situation.

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### ***Personal Communications***

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Julien, N (2005) Syngenta SAS, 22 Rue Morat, 78212 Saint Cyr l'Ecole. France

Treil, D (2001) Owner of the Villarzel-Cabardes site, Aude. France

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## **Appendix 1**

### **Visual Soil Assessment Techniques**

*(The following excerpts and plates are taken from Shepherd, 2000)*

“The VSA method is based on the visual assessment of key soil ‘state’ and plant ‘performance’ indicators of soil quality, presented on a score card. Soil quality is ranked by assessment of the soil quality indicators alone. It does not require knowledge of crop history.”

“Each indicator is given a visual score (VS) of 0 (poor), 1 (moderate), or 2 (good), based on the soil quality observed when comparing the field sample with the photographs in the field guide. The scoring is flexible, so if the sample you are assessing does not clearly align with any one of the photographs but sits between two, a score in between can be given, for example 0.5 or 1.5. An explanation of the scoring criteria accompanies each set of photographs.”

“Because some soil factors or indicators are relatively more important for soil quality than others, VSA provides a weighting factor of 1, 2 or 3. For example, soil structure is a more important indicator (a factor of 3) than clod development (a factor of 1). The score you give each indicator is multiplied by the weighting factor to give a VS ranking. The total of the VS rankings gives the overall ranking score for the sample you are assessing. Compare this with the score ranges at the bottom of the page to determine whether your soil has good, moderate or poor soil quality.”

“VSA can be carried out effectively and reliably over a range of soil moisture levels. However, we suggest that you carry out the VSA when you judge that the soil is at the correct moisture content for cultivation, or is sufficiently dry to prevent compaction and pugging by wheel traffic and stock treading.”

#### *“Soil structure and consistence*

- Remove a 20 cm cube of topsoil with a spade.
- Drop the soil sample a maximum of three times from a height of one metre (waist height) on to a firm base in a plastic basin. If large clods break away after the first or second drop, drop them individually again once or twice. If a clod shatters into small (primary structural) units after the first or second drop, it does not need dropping again. Don’t drop any piece of soil more than three times.
- Separate each clod from enmeshing roots, and part it by hand along any exposed fracture planes or fissures.
- Transfer the soil onto a large plastic bag.
- Move the coarsest fractions to one end and the finest to the other end. This provides a measure of the aggregate-size distribution. Compare the resulting distribution of aggregates with the three photographs.”

#### *“Soil porosity*

- Remove a spade slice of soil from the side of the hole created by taking the 20 cm cube of topsoil, or take a number of clods from the aggregate distribution test.
- Examine for soil porosity, comparing with the three photographs.”

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*“Soil colour*

- Compare the colour of a handful of soil from the soil structure test with soil taken from under the nearest fence line.
- Using the three photographs below, compare the relative change in soil colour that has occurred.

As topsoil colour can vary between soil types, the photographs illustrate the trend rather than the absolute colour of the soil.”

*“Number and colour of soil mottles*

- Assess the number and colour of mottles by comparing the side of the soil profile, or a number of soil clods from the soil structure test, with the three photographs.”

*“Earthworm counts*

Sort carefully through the soil sample used to assess soil structure, and count the earthworms found in a five minute search. Earthworms vary in size and in number depending on the season, so for year-to-year comparison earthworm counts must be made at the same time of year, and preferably during the winter. The class limits for earthworm numbers given are based on the probability that you will find only two-thirds of the worms present during a five minute search.”

| Visual score<br>(VS) | Earthworm counts<br>(per 20 cm cube of soil) |
|----------------------|----------------------------------------------|
| 2                    | >8                                           |
| 1                    | 4-8                                          |
| 0                    | <4                                           |

*“Presence of a tillage pan*

- Examine the lower part of the topsoil and compare with the upper topsoil. This can be done in situ or by removing a spade slice from the side of the hole exposed by removing the 20 cm cube extracted for the structural assessment.
- Compare against the photographs.

*“Degree of clod development*

- Assess the degree of clodding on the soil surface between rows by comparing it against the photographs.
- Consider also the amount of tillage and time that was required to prepare the seedbed. Some soil clods may slake during rainfall so, to be meaningful, several assessments should be made.”

## Soil structure & consistence



**GOOD CONDITION VS = 2**  
Good distribution of friable finer aggregates with no significant clodding



**MODERATE CONDITION VS = 1**  
Soil contains significant proportions of both coarse firm clods and friable, fine aggregates



**POOR CONDITION VS = 0**  
Soil dominated by extremely coarse, very firm clods with very few finer aggregates

## Soil porosity



**GOOD CONDITION VS = 2**  
Soils have many macropores between and within aggregates associated with readily apparent good soil structure



**MODERATE CONDITION VS = 1**  
Soil macropores between and within aggregates have declined significantly but are present on close examination of clods showing a moderate amount of consolidation



**POOR CONDITION VS = 0**  
No macropores or coarse micropores are visually apparent within compact, massive structureless clods that typically show smooth faces with sharp angles, and have few cracks or holes

## Soil colour



**GOOD CONDITION VS = 2**  
Dark coloured topsoil indicating a well-aerated soil with a good turnover of organic matter



**MODERATE CONDITION VS = 1**  
The colour of the topsoil is somewhat paler due to the early stages of gleying because of moderate pugging



**POOR CONDITION VS = 0**  
Soil colour has become significantly paler due to gleying because of persistent pugging

## Number & colour of soil mottles



**GOOD CONDITION VS = 2**  
Mottles are generally absent



**MODERATE CONDITION VS = 1**  
Soil has common (10-25%) fine and medium orange and grey mottles



**POOR CONDITION VS = 0**  
Soil has abundant to profuse (>50%), medium and coarse orange and grey mottles

## Presence of a tillage pan



**GOOD CONDITION VS = 2**  
No tillage pan with a friable, clearly apparent structure and soil pores throughout the topsoil



**MODERATE CONDITION VS = 1**  
Firm, moderately developed tillage pan in the lower topsoil showing clear zones of consolidation but including areas with weakly developed structure, cracks, fissures and a few macropores



**POOR CONDITION VS = 0**  
Very firm to hard, well-developed tillage pan in the lower topsoil, showing severe consolidation with no structure, no macropores and few or no cracks

## Degree of clod development



**GOOD CONDITION VS = 2**  
Good distribution of the friable, finer aggregates with no significant clodding. A good seedbed is readily prepared



**MODERATE CONDITION VS = 1**  
Soil contains significant proportions of both coarse firm clods and friable, fine aggregates. If cultivation is not carefully timed, clods show significant tillage resistance



**POOR CONDITION VS = 0**  
Soil dominated by coarse, very firm clods with fewer finer aggregates. Clod resistance is high and the window for cultivation is very narrow

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## Appendix 2

### Data behind graphs in Chapter 4

Table A – 1

Data behind figure 4.2: Sediment losses over the life of the project

| Sampling period | Estimated sediment loss (kg m <sup>-2</sup> ) |             |
|-----------------|-----------------------------------------------|-------------|
|                 | Conventional                                  | Alternative |
| 1               | 0.02                                          | 0.06        |
| 2               | 0.01                                          | 0.05        |
| 3               | 0.03                                          | 0.20        |
| 4               | 2.17                                          | 3.75        |
| 5               | 2.05                                          | 1.67        |
| 6               | 4.51                                          | 4.56        |
| 7               | 0.50                                          | 0.23        |
| 8               | 2.42                                          | 0.33        |
| 10              | 2.01                                          | 0.56        |
| 11              | 0.27                                          | 0.18        |
| 12              | 1.17                                          | 0.48        |
| 14              | 0.03                                          | 0.00        |
| 15              | 0.00                                          | 0.00        |
| 17              | 0.65                                          | 0.02        |
| 18              | 0.69                                          | 0.14        |

Table A – 2

Data behind Figure 4.3: Runoff losses over the life of the project

| Sampling period | Estimated runoff loss (l m <sup>-2</sup> ) |             |
|-----------------|--------------------------------------------|-------------|
|                 | Conventional                               | Alternative |
| 1               | 38.24                                      | 17.38       |
| 2               | 22.33                                      | 13.20       |
| 3               | 37.16                                      | 29.34       |
| 4               | 38.20                                      | 42.84       |
| 5               | 24.74                                      | 24.51       |
| 6               | 22.30                                      | 66.45       |
| 7               | 12.22                                      | 18.94       |
| 8               | 25.17                                      | 33.28       |
| 10              | 49.86                                      | 54.22       |
| 11              | 22.56                                      | 43.73       |
| 12              | 84.53                                      | 84.54       |
| 14              | 48.36                                      | 32.62       |
| 15              | 13.35                                      | 4.30        |
| 17              | 4.34                                       | 4.32        |
| 18              | 41.57                                      | 39.90       |

*Table A – 3*  
*Data behind Figure 4.4: TKE and sediment losses throughout the life of the project*

| Sampling period | Sediment (kg m <sup>-2</sup> ) |             | TKE (j m <sup>-2</sup> ) |
|-----------------|--------------------------------|-------------|--------------------------|
|                 | Conventional                   | Alternative |                          |
| 1               | 0.02                           | 0.06        | 1247.12                  |
| 2               | 0.01                           | 0.05        | 1054.56                  |
| 3               | 0.03                           | 0.2         | 1697.23                  |
| 4               | 2.17                           | 3.75        | 1046.42                  |
| 5               | 2.05                           | 1.67        | 1575.7                   |
| 7               | 4.51                           | 4.56        | 7042.01                  |
| 8               | 0.5                            | 0.23        | 1533.81                  |
| 10              | 2.01                           | 0.56        | 1723.91                  |
| 11              | 0.27                           | 0.18        | 1235.61                  |
| 12              | 1.17                           | 0.48        | 3966.86                  |
| 14              | 0.03                           | 0           | 796.1                    |
| 15              | 0                              | 0           | 1640.22                  |
| 17              | 0.65                           | 0.02        | 1722.08                  |
| 18              | 0.69                           | 0.14        | 2286.05                  |

*Table A – 4*  
*Data behind Figure 4.5: Sediment / TKE relationship for establishment phase 1*

| Sediment (kg m <sup>-2</sup> ) |             | TKE (j m <sup>-2</sup> ) |
|--------------------------------|-------------|--------------------------|
| Conventional                   | Alternative |                          |
| 0.02                           | 0.06        | 1247.12                  |
| 0.01                           | 0.05        | 1054.56                  |
| 0.03                           | 0.2         | 1697.23                  |
| 2.17                           | 3.75        | 1046.42                  |

*Table A – 5*  
*Data behind Figure 4.6: Sediment / TKE relationship for establishment phase 2*

| Sediment (kg m <sup>-2</sup> ) |             | TKE (j m <sup>-2</sup> ) |
|--------------------------------|-------------|--------------------------|
| Conventional                   | Alternative |                          |
| 2.05                           | 1.67        | 1575.7                   |
| 4.51                           | 4.56        | 7042.01                  |
| 0.5                            | 0.23        | 1533.81                  |
| 2.01                           | 0.56        | 1723.91                  |
| 0.27                           | 0.18        | 1235.61                  |
| 1.17                           | 0.48        | 3966.86                  |

*Table A – 6*  
*Data behind Figure 4.7: Sediment / TKE relationship for establishment phase 3*

| Sediment (kg m <sup>-2</sup> ) |             | TKE (j m <sup>-2</sup> ) |
|--------------------------------|-------------|--------------------------|
| Conventional                   | Alternative |                          |
| 0.03                           | 0           | 796.1                    |
| 0                              | 0           | 1640.22                  |
| 0.65                           | 0.02        | 1722.08                  |
| 0.69                           | 0.14        | 2286.05                  |

*Table A – 7*  
*Data behind Figure 4.8: Rainfall / runoff loss relationship for the alternative treatment*

| Sampling period | Estimated total runoff (l m <sup>-2</sup> ) |             | Significant rain (mm) |
|-----------------|---------------------------------------------|-------------|-----------------------|
|                 | Conventional                                | Alternative |                       |
| 1               | 38.24                                       | 17.38       | 83.4                  |
| 2               | 22.33                                       | 13.20       | 68.2                  |
| 3               | 37.16                                       | 29.34       | 108.6                 |
| 4               | 38.20                                       | 42.84       | 55.4                  |
| 5               | 24.74                                       | 24.51       | 87.6                  |
| 7               | 22.30                                       | 66.45       | 423.8                 |
| 8               | 12.22                                       | 18.94       | 98.2                  |
| 10              | 49.86                                       | 54.22       | 101.8                 |
| 11              | 22.56                                       | 43.73       | 98                    |
| 12              | 84.53                                       | 84.54       | 235                   |
| 14              | 48.36                                       | 32.62       | 95.8                  |
| 15              | 13.35                                       | 4.30        | 132.8                 |
| 17              | 4.34                                        | 4.32        | 109.8                 |
| 18              | 41.57                                       | 39.90       | 186.4                 |

*Table A – 8*  
*Data behind Figure 4.9: Sediment losses over the life of the project*

| Sampling period | Estimated sediment loss (kg m <sup>-2</sup> ) |             |
|-----------------|-----------------------------------------------|-------------|
|                 | Conventional                                  | Alternative |
| 2               | 0.17                                          | 0.46        |
| 3               | 0.01                                          | 0.07        |
| 4               | 1.73                                          | 0.63        |
| 6               | 0.00                                          | 0.00        |
| 7               | 0.01                                          | 0.02        |
| 8               | 0.01                                          | 0.04        |
| 10              | 0.12                                          | 0.01        |
| 11              | 0.87                                          | 0.03        |
| 12              | 0.04                                          | 0.00        |
| 13              | 0.11                                          | 0.01        |
| 14              | 1.26                                          | 0.02        |

*Table A – 9*  
*Data behind Figure 4.10: Runoff losses over the life of the project*

| Sampling period | Estimated runoff loss (l m <sup>-2</sup> ) |             |
|-----------------|--------------------------------------------|-------------|
|                 | Conventional                               | Alternative |
| 2               | 4.68                                       | 18.44       |
| 3               | 1.35                                       | 8.56        |
| 4               | 25.30                                      | 55.11       |
| 6               | 3.75                                       | 5.57        |
| 7               | 4.51                                       | 8.09        |
| 8               | 1.66                                       | 12.16       |
| 10              | 43.25                                      | 13.76       |
| 11              | 8.98                                       | 8.58        |
| 12              | 15.35                                      | 12.69       |
| 13              | 4.88                                       | 8.60        |
| 14              | 12.88                                      | 11.70       |

*Table A – 10*  
*Data behind Figure 4.11: TKE and sediment losses throughout the life of the project*

| Sampling period | Sediment (kg m <sup>-2</sup> ) |             | TKE (j m <sup>-2</sup> ) |
|-----------------|--------------------------------|-------------|--------------------------|
|                 | Conventional                   | Alternative |                          |
| 2               | 0.17                           | 0.46        | 1392.73                  |
| 3               | 0.01                           | 0.07        | 806.30                   |
| 4               | 1.73                           | 0.63        | 1801.56                  |
| 6               | 0.00                           | 0.00        | 1701.77                  |
| 7               | 0.01                           | 0.02        | 1761.13                  |
| 8               | 0.01                           | 0.04        | 943.69                   |
| 10              | 0.12                           | 0.01        | 1842.77                  |
| 11              | 0.87                           | 0.03        | 972.29                   |
| 12              | 0.04                           | 0.00        | 1307.13                  |
| 13              | 0.11                           | 0.01        | 1557.40                  |
| 14              | 1.26                           | 0.02        | 746.53                   |

*Table A -11*  
*Data behind Figure 4.12: Sediment / TKE relationship for establishment phase 2*

| Sediment (kg m <sup>-2</sup> ) |             | TKE (j m <sup>-2</sup> ) |
|--------------------------------|-------------|--------------------------|
| Conventional                   | Alternative |                          |
| 1.73                           | 0.63        | 1801.56                  |
| 0.00                           | 0.00        | 1701.77                  |
| 0.01                           | 0.02        | 1761.13                  |
| 0.01                           | 0.04        | 943.69                   |

*Table A - 12*  
*Data behind Figure 4.13: Sediment / TKE relationship for establishment phase 3*

| Sediment (kg m <sup>-2</sup> ) |             | TKE (j m <sup>-2</sup> ) |
|--------------------------------|-------------|--------------------------|
| Conventional                   | Alternative |                          |
| 0.12                           | 0.01        | 1842.77                  |
| 0.87                           | 0.03        | 972.29                   |
| 0.04                           | 0.00        | 1307.13                  |
| 0.11                           | 0.01        | 1557.40                  |
| 1.26                           | 0.02        | 746.53                   |

*Table A – 13*  
*Data behind Figure 4.14: Rainfall / runoff loss relationships*

| Sampling period | Estimated total runoff (l m <sup>-2</sup> ) |             | Significant rain (mm) |
|-----------------|---------------------------------------------|-------------|-----------------------|
|                 | Conventional                                | Alternative |                       |
| 2               | 4.68                                        | 18.44       | 112.8                 |
| 3               | 1.35                                        | 8.56        | 47.6                  |
| 4               | 25.30                                       | 55.11       | 119.4                 |
| 6               | 3.75                                        | 5.57        | 182                   |
| 7               | 4.51                                        | 8.09        | 95.8                  |
| 8               | 1.66                                        | 12.16       | 52.2                  |
| 10              | 43.25                                       | 13.76       | 442.8                 |
| 11              | 8.98                                        | 8.58        | 74                    |
| 12              | 15.35                                       | 12.69       | 113.2                 |
| 13              | 4.88                                        | 8.60        | 88.6                  |
| 14              | 12.88                                       | 11.70       | 51                    |

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## Appendix 3

### *Genstat output for the experiments described in Chapter 5*

Variate: %\_cover\_1\_DAA

| Source of variation | d.f. | s.s.   | m.s.  | v.r. | F pr. |
|---------------------|------|--------|-------|------|-------|
| Dose                | 4    | 80.00  | 20.00 | 1.20 | 0.342 |
| Product             | 1    | 13.33  | 13.33 | 0.80 | 0.382 |
| Dose.Product        | 4    | 53.33  | 13.33 | 0.80 | 0.539 |
| Residual            | 20   | 333.33 | 16.67 |      |       |
| Total               | 29   | 480.00 |       |      |       |

Variate: %\_cover\_7\_DAA

| Source of variation | d.f. | s.s.    | m.s.   | v.r. | F pr. |
|---------------------|------|---------|--------|------|-------|
| Dose                | 4    | 500.00  | 125.00 | 2.63 | 0.065 |
| Product             | 1    | 120.00  | 120.00 | 2.53 | 0.128 |
| Dose.Product        | 4    | 446.67  | 111.67 | 2.35 | 0.089 |
| Residual            | 20   | 950.00  | 47.50  |      |       |
| Total               | 29   | 2016.67 |        |      |       |

Variate: %\_cover\_14\_DAA

| Source of variation | d.f. | s.s.    | m.s.   | v.r.  | F pr. |
|---------------------|------|---------|--------|-------|-------|
| Dose                | 4    | 3380.00 | 845.00 | 18.11 | <.001 |
| Product             | 1    | 163.33  | 163.33 | 3.50  | 0.076 |
| Dose.Product        | 4    | 220.00  | 55.00  | 1.18  | 0.350 |
| Residual            | 20   | 933.33  | 46.67  |       |       |
| Total               | 29   | 4696.67 |        |       |       |

Variate: %\_Cover\_21\_DAA

| Source of variation | d.f. | s.s.    | m.s.    | v.r.   | F pr. |
|---------------------|------|---------|---------|--------|-------|
| Dose                | 4    | 6553.33 | 1638.33 | 122.88 | <.001 |
| Product             | 1    | 53.33   | 53.33   | 4.00   | 0.059 |
| Dose.Product        | 4    | 46.67   | 11.67   | 0.87   | 0.496 |
| Residual            | 20   | 266.67  | 13.33   |        |       |
| Total               | 29   | 6920.00 |         |        |       |

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Variate: Herb\_effect\_1\_DAA\_%

| Source of variation | d.f. | s.s.     | m.s.     | v.r.    | F pr. |
|---------------------|------|----------|----------|---------|-------|
| Dose                | 4    | 12828.33 | 3207.08  | 274.89  | <.001 |
| Product             | 1    | 19763.33 | 19763.33 | 1694.00 | <.001 |
| Dose.Product        | 4    | 12445.00 | 3111.25  | 266.68  | <.001 |
| Residual            | 20   | 233.33   | 11.67    |         |       |
| Total               | 29   | 45270.00 |          |         |       |

Variate: Herb\_effect\_7\_DAA\_%

| Source of variation | d.f. | s.s.    | m.s.   | v.r.  | F pr. |
|---------------------|------|---------|--------|-------|-------|
| Dose                | 4    | 34771.7 | 8692.9 | 42.23 | <.001 |
| Product             | 1    | 3967.5  | 3967.5 | 19.28 | <.001 |
| Dose.Product        | 4    | 4528.3  | 1132.1 | 5.50  | 0.004 |
| Residual            | 20   | 4116.7  | 205.8  |       |       |
| Total               | 29   | 47384.2 |        |       |       |

Variate: Herb\_effect\_14\_DAA\_%

| Source of variation | d.f. | s.s.     | m.s.     | v.r.   | F pr. |
|---------------------|------|----------|----------|--------|-------|
| Dose                | 4    | 44393.53 | 11098.38 | 217.76 | <.001 |
| Product             | 1    | 1165.63  | 1165.63  | 22.87  | <.001 |
| Dose.Product        | 4    | 3104.20  | 776.05   | 15.23  | <.001 |
| Residual            | 20   | 1019.33  | 50.97    |        |       |
| Total               | 29   | 49682.70 |          |        |       |

Variate: Herb\_effect\_21\_DAA\_%

| Source of variation | d.f. | s.s.     | m.s.     | v.r.   | F pr. |
|---------------------|------|----------|----------|--------|-------|
| Dose                | 4    | 43996.67 | 10999.17 | 628.52 | <.001 |
| Product             | 1    | 300.83   | 300.83   | 17.19  | <.001 |
| Dose.Product        | 4    | 1086.67  | 271.67   | 15.52  | <.001 |
| Residual            | 20   | 350.00   | 17.50    |        |       |
| Total               | 29   | 45734.17 |          |        |       |

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Variate: Biomass\_g\_cm2

| Source of variation | d.f. | s.s.      | m.s.      | v.r.  | F pr. |
|---------------------|------|-----------|-----------|-------|-------|
| Product             | 1    | 2.236E-05 | 2.236E-05 | 17.26 | <.001 |
| Dose                | 4    | 4.074E-04 | 1.019E-04 | 78.63 | <.001 |
| Product.Dose        | 4    | 1.365E-04 | 3.413E-05 | 26.35 | <.001 |
| Residual            | 20   | 2.591E-05 | 1.295E-06 |       |       |
| Total               | 29   | 5.922E-04 |           |       |       |

Variate: K\_m\_d (permeability)

| Source of variation | d.f. | s.s.    | m.s.    | v.r. | F pr. |
|---------------------|------|---------|---------|------|-------|
| Product             | 1    | 0.00000 | 0.00000 | 0.00 | 0.992 |
| Dose                | 4    | 0.11313 | 0.02828 | 1.36 | 0.282 |
| Product.Dose        | 4    | 0.07328 | 0.01832 | 0.88 | 0.492 |
| Residual            | 20   | 0.41502 | 0.02075 |      |       |
| Total               | 29   | 0.60144 |         |      |       |

Variate: OM\_%

| Source of variation | d.f. | s.s.    | m.s.    | v.r. | F pr. |
|---------------------|------|---------|---------|------|-------|
| Product             | 1    | 0.08806 | 0.08806 | 2.51 | 0.129 |
| Dose                | 4    | 0.23586 | 0.05897 | 1.68 | 0.194 |
| Product.Dose        | 4    | 0.13059 | 0.03265 | 0.93 | 0.467 |
| Residual            | 20   | 0.70218 | 0.03511 |      |       |
| Total               | 29   | 1.15669 |         |      |       |

Variate: Root\_density\_g\_cm3

| Source of variation | d.f. | s.s.      | m.s.      | v.r.  | F pr. |
|---------------------|------|-----------|-----------|-------|-------|
| Product             | 1    | 2.613E-07 | 2.613E-07 | 2.34  | 0.142 |
| Dose                | 4    | 5.655E-06 | 1.414E-06 | 12.66 | <.001 |
| Product.Dose        | 4    | 3.853E-07 | 9.633E-08 | 0.86  | 0.503 |
| Residual            | 20   | 2.233E-06 | 1.117E-07 |       |       |
| Total               | 29   | 8.535E-06 |           |       |       |

Variate: Shear\_strength\_kg\_cm2

| Source of variation | d.f. | s.s.     | m.s.     | v.r. | F pr. |
|---------------------|------|----------|----------|------|-------|
| Product             | 1    | 0.000403 | 0.000403 | 0.14 | 0.713 |
| Dose                | 4    | 0.030767 | 0.007692 | 2.65 | 0.063 |
| Product.Dose        | 4    | 0.011047 | 0.002762 | 0.95 | 0.455 |
| Residual            | 20   | 0.058000 | 0.002900 |      |       |
| Total               | 29   | 0.100217 |          |      |       |

*Table A – 14*  
Mean & standard error of treatment effects on soil permeability, 21 days after application

| Product | Dose (l ha <sup>-1</sup> ) | Mean (m d <sup>-1</sup> ) | SD       | SEM      |
|---------|----------------------------|---------------------------|----------|----------|
| G       | 0                          | 0.165183                  | 0.224703 | 0.129886 |
| G       | 0.75                       | 0.161541                  | 0.124989 | 0.072248 |
| G       | 1.5                        | 0.158702                  | 0.123546 | 0.071414 |
| G       | 3                          | 0.116028                  | 0.041932 | 0.024238 |
| G       | 5                          | 0.081621                  | 0.031231 | 0.018053 |
| TD      | 0                          | 0.06109                   | 0.057477 | 0.033224 |
| TD      | 0.75                       | 0.145669                  | 0.117743 | 0.06806  |
| TD      | 1.5                        | 0.338596                  | 0.322363 | 0.186337 |
| TD      | 3                          | 0.04401                   | 0.003179 | 0.001837 |
| TD      | 4                          | 0.096505                  | 0.048024 | 0.027759 |

*Table A – 15*  
Mean & standard error of treatment effects on soil organic matter, 21 days after application

| Product | Dose (l ha <sup>-1</sup> ) | Mean (%) | SD       | SEM      |
|---------|----------------------------|----------|----------|----------|
| G       | 0                          | 6.043682 | 0.197184 | 0.113979 |
| G       | 0.75                       | 6.133236 | 0.171551 | 0.099162 |
| G       | 1.5                        | 5.962621 | 0.133875 | 0.077384 |
| G       | 3                          | 5.930837 | 0.211114 | 0.122031 |
| G       | 5                          | 6.049266 | 0.095907 | 0.055437 |
| TD      | 0                          | 5.984209 | 0.119869 | 0.069288 |
| TD      | 0.75                       | 6.066889 | 0.226768 | 0.13108  |
| TD      | 1.5                        | 5.707998 | 0.164887 | 0.095311 |
| TD      | 3                          | 6.023333 | 0.223533 | 0.12921  |
| TD      | 4                          | 5.795419 | 0.261037 | 0.150889 |

*Table A – 16*  
*Mean & standard error of treatment effects on soil shear strength, 21 days after application*

| Product | Dose (l ha <sup>-1</sup> ) | Mean (kg cm <sup>-2</sup> ) | SD       | SEM      |
|---------|----------------------------|-----------------------------|----------|----------|
| G       | 0                          | 0.119167                    | 0.058748 | 0.033958 |
| G       | 0.75                       | 0.112567                    | 0.052712 | 0.030469 |
| G       | 1.5                        | 0.065267                    | 0.040586 | 0.02346  |
| G       | 3                          | 0.067833                    | 0.049906 | 0.028847 |
| G       | 5                          | 0.113667                    | 0.045118 | 0.02608  |
| TD      | 0                          | 0.077                       | 0.004795 | 0.002772 |
| TD      | 0.75                       | 0.123567                    | 0.030031 | 0.017359 |
| TD      | 1.5                        | 0.083967                    | 0.059322 | 0.03429  |
| TD      | 3                          | 0.043267                    | 0.010221 | 0.005908 |
| TD      | 4                          | 0.1848                      | 0.110412 | 0.063822 |

### **Data behind graphs in Chapter 5**

*Table A – 17*  
*Data behind Figure 5.1: Mean & standard error of treatment effects on dry root density, 21 days after application*

| Product | Dose (l ha <sup>-1</sup> ) | Mean (g cm <sup>-3</sup> ) | SD                      | SEM                        |
|---------|----------------------------|----------------------------|-------------------------|----------------------------|
| G       | 0                          | 0.002381                   | 0.000123                | 7.08782 x 10 <sup>-5</sup> |
| G       | 0.75                       | 0.001237                   | 0.000248                | 0.000143574                |
| G       | 1.5                        | 0.001171                   | 0.000208                | 0.0001205                  |
| G       | 3                          | 0.001432                   | 0.000606                | 0.000350011                |
| G       | 5                          | 0.001054                   | 7.99 x 10 <sup>-5</sup> | 4.61692 x 10 <sup>-5</sup> |
| TD      | 0                          | 0.002365                   | 0.000435                | 0.000251295                |
| TD      | 0.75                       | 0.001783                   | 0.000345                | 0.000199191                |
| TD      | 1.5                        | 0.001448                   | 0.000325                | 0.000187783                |
| TD      | 3                          | 0.001310                   | 0.000431                | 0.00024917                 |
| TD      | 4                          | 0.001207                   | 0.000255                | 0.000147221                |

*Table A – 18*  
*Data behind Figure 5.2: Mean & standard error of treatment effects on surface biomass, 21 days after application*

| Product | Dose (l ha <sup>-1</sup> ) | Mean (g cm <sup>-2</sup> ) | SD     | SEM                     |
|---------|----------------------------|----------------------------|--------|-------------------------|
| G       | 0                          | 0.0234                     | 0.0019 | 0.001098                |
| G       | 0.75                       | 0.0106                     | 0.0007 | 0.000407                |
| G       | 1.5                        | 0.0114                     | 0.0017 | 0.000978                |
| G       | 3                          | 0.0106                     | 0.0008 | 0.000478                |
| G       | 5                          | 0.0116                     | 0.0001 | 4.47 x 10 <sup>-5</sup> |
| TD      | 0                          | 0.0191                     | 0.0002 | 9.45 x 10 <sup>-5</sup> |
| TD      | 0.75                       | 0.0187                     | 0.0011 | 0.000654                |
| TD      | 1.5                        | 0.0158                     | 0.0008 | 0.000485                |
| TD      | 3                          | 0.0122                     | 0.0012 | 0.000688                |
| TD      | 4                          | 0.0105                     | 0.0013 | 0.00074                 |

*Table A – 19*  
*Data behind Figure 5.3: Mean & standard error of % desiccation with time after application with Touchdown*

| Time<br>(DAA) | Dose (l ha <sup>-1</sup> ) |     |      |     |      |     |      |     |      |     |
|---------------|----------------------------|-----|------|-----|------|-----|------|-----|------|-----|
|               | 0                          |     | 0.75 |     | 1.5  |     | 3    |     | 4    |     |
|               | Mean                       | SEM | Mean | SEM | Mean | SEM | Mean | SEM | Mean | SEM |
| 1             | 0                          | 0   | 0    | 0   | 0    | 0   | 2    | 2   | 0    | 0   |
| 7             | 0                          | 0   | 5    | 0   | 27   | 3   | 95   | 0   | 98   | 2   |
| 14            | 0                          | 0   | 10   | 0   | 65   | 13  | 99   | 1   | 100  | 0   |
| 21            | 0                          | 0   | 23   | 3   | 72   | 6   | 100  | 0   | 100  | 0   |

*Table A – 20*  
*Data behind Figure 5.4: Mean & standard error of % desiccation with time after application with Gramoxone*

| Time<br>(DAA) | Dose (l ha <sup>-1</sup> ) |     |      |     |      |     |      |     |      |     |
|---------------|----------------------------|-----|------|-----|------|-----|------|-----|------|-----|
|               | 0                          |     | 0.75 |     | 1.5  |     | 3    |     | 5    |     |
|               | Mean                       | SEM | Mean | SEM | Mean | SEM | Mean | SEM | Mean | SEM |
| 1             | 0                          | 0   | 8    | 2   | 60   | 6   | 90   | 0   | 100  | 0   |
| 7             | 0                          | 0   | 50   | 0   | 82   | 2   | 87   | 2   | 95   | 0   |
| 14            | 0                          | 0   | 57   | 3   | 90   | 0   | 95   | 0   | 95   | 0   |
| 21            | 0                          | 0   | 50   | 0   | 85   | 3   | 95   | 0   | 97   | 2   |

*Table A – 21*  
*Data behind Figure 5.5: Mean & standard error of % cover over time after application with Touchdown*

| Time<br>(DAA) | Dose (l ha <sup>-1</sup> ) |     |      |     |      |     |      |     |      |     |
|---------------|----------------------------|-----|------|-----|------|-----|------|-----|------|-----|
|               | 0                          |     | 0.75 |     | 1.5  |     | 3    |     | 4    |     |
|               | Mean                       | SEM | Mean | SEM | Mean | SEM | Mean | SEM | Mean | SEM |
| 1             | 50                         | 0   | 50   | 0   | 50   | 0   | 53   | 3   | 53   | 3   |
| 7             | 53                         | 3   | 53   | 3   | 47   | 2   | 40   | 0   | 50   | 6   |
| 14            | 60                         | 0   | 50   | 0   | 40   | 6   | 23   | 3   | 37   | 7   |
| 21            | 60                         | 0   | 50   | 0   | 37   | 3   | 20   | 0   | 20   | 0   |

*Table A – 22*  
*Data behind Figure 5.6: Mean & standard error of % cover over time after application with Gramoxone*

| Time<br>(DAA) | Dose (l ha <sup>-1</sup> ) |     |      |     |      |     |      |     |      |     |
|---------------|----------------------------|-----|------|-----|------|-----|------|-----|------|-----|
|               | 0                          |     | 0.75 |     | 1.5  |     | 3    |     | 5    |     |
|               | Mean                       | SEM | Mean | SEM | Mean | SEM | Mean | SEM | Mean | SEM |
| 1             | 50                         | 0   | 50   | 0   | 57   | 3   | 53   | 3   | 53   | 3   |
| 7             | 50                         | 0   | 37   | 3   | 53   | 7   | 40   | 6   | 43   | 3   |
| 14            | 50                         | 0   | 43   | 3   | 40   | 6   | 27   | 3   | 27   | 3   |
| 21            | 53                         | 3   | 47   | 3   | 33   | 3   | 20   | 0   | 20   | 0   |

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*Table A – 23*  
*Data behind figure 5.7: Treatment effects on the desiccation / cover relationship, 21 days after application*

| Product / dose             | % herbicide effect | SEM | % cover | SEM |
|----------------------------|--------------------|-----|---------|-----|
| G 0 l ha <sup>-1</sup>     | 0                  | 0   | 53      | 3   |
| G 0.75 l ha <sup>-1</sup>  | 50                 | 0   | 47      | 3   |
| G 1.5 l ha <sup>-1</sup>   | 85                 | 3   | 33      | 3   |
| G 3 l ha <sup>-1</sup>     | 95                 | 0   | 20      | 0   |
| G 5 l ha <sup>-1</sup>     | 97                 | 2   | 20      | 0   |
| TD 0 l ha <sup>-1</sup>    | 0                  | 0   | 60      | 0   |
| TD 0.75 l ha <sup>-1</sup> | 23                 | 3   | 50      | 0   |
| TD 1.5 l ha <sup>-1</sup>  | 72                 | 6   | 37      | 3   |
| TD 3 l ha <sup>-1</sup>    | 100                | 0   | 20      | 0   |
| TD 4 l ha <sup>-1</sup>    | 100                | 0   | 20      | 0   |