Aeolian Sediment Transport and Direct Drilling under Semi-arid Conditions in the South Island, New Zealand

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Abstract: Large areas of the South Island, New Zealand, are affected by strong winds. These are predominantly from the west or south and, in poorly vegetated landscapes, they can contribute to aeolian transport of substantial amounts of sediment. The severity of this semi-arid environment places great stress on introduced and native pasture species and can result in poor establishment of new pastures using standard drilling techniques.

Following previous drilling trials, an investigation utilizing strip seeder technology was established in 1999 to ascertain the effect of drilling on wind-borne sediment transport and the sub-soil environment. Drought-tolerant forage species established were wheatgrass (*Thinopyron intermedium*), tall oat grass (*Arrhenatherum elatius*), birdsfoot trefoil (*Lotus corniculatus*), hairy dorycnium (*Dorycnium hirsutum*) and cocksfoot (*Dactylis glomerata*).

Sedimentation processes and measurement equipment are discussed. Preliminary data from monitoring of aeolian sediment transport using deposition, saltation and Fryrear traps, sampled at monthly intervals, are presented together with meteorological and sediment capture data for the period covering July 2000 to end February 2001. Results from the saltation traps indicate that sediment movement within the bare sprayed/drilled plots (averaging 1 g—2 g per linear metre per day) was 2—4 times greater than that within the drilled/vegetated plots.
Keywords: aeolian sediment transport, El Nino, forage species, semi-arid pasture, strip-seeder drill, wind erosion

1 Introduction and methods

A novel strip seeder drill and a standard hoe coulter drill were compared for semi-arid pasture establishment in Central Otago during 1998—2000. Superior establishment was shown with the strip seeder drill on dryland sites even during adverse drought conditions (Wills and Trainor, in preparation). The objective of this investigation was to determine the effectiveness of selected forage plants established with the strip seeder drill and appropriate management in providing persistent ground cover, thereby preventing wind erosion. If achieved, the potential to reduce sediment loss from South Island semi-arid tussock grasslands prone to wind erosion may be realized, at least in part.

The project is sited on a typical alluvial terrace (altitude = 280m ASL) near Cromwell, Central Otago, on Waenga Station (InfoMap 260-G41, 120655). Aspect is flat and the site is exposed to the north-west and the south, the direction of the prevailing winds. The Lowburn soil is a brown-grey earth, (now known as an argillic semi-arid soil: Hewitt 1998) formed on old alluvium with some loessial patches. Plant available water to 20cm depth is 45mm. Soil bulk density is 1.3 t/m^3—1.4 t/m^3 (0 mm—100 mm depth).

Long-term meteorological data (1949—1980) attributable to the nearest official site, Cromwell (1984—2001 means in brackets) are:

Mean Annual Rainfall = 401 mm (453 mm)
Raised Pan Evaporation = no record (1,428 mm)
Mean Annual Air Temperature =10.8℃ Max 33.0℃, Min –7.7℃, Daily Max 16.8℃,Min 4.8℃
(10.8℃ Max 32.5℃, Min –7.4℃, Daily Max 16.9℃, Min 4.6℃)
Mean Annual Grass Minimum Temperature = –0.1℃ (1.4℃)

Mean Annual Ground Frost Days = 174 (110)

Mean Annual Relative Humidity = 74% (78%)

The trial was established in September 1999 and is approximately 1 ha in size and fenced to exclude rabbits and stock. There are three replicates, each with ten randomly allocated plots. Eight plots were drilled with the strip-seeder and two were left as undisturbed controls (resident vegetation plus and minus fertilizer). Five of the drilled plots were fertilized and seeded with the drought-tolerant forage species: wheatgrass (*Thinopyron intermedium*), tall oat grass (*Arrhenatherum elatius*), birdsfoot trefoil (*Lotus corniculatus*), hairy dorycnium (*Dorycnium hirsutum*) and cocksfoot (*Dactylis glomerata*). The remaining three plots were drilled and unseeded with nil, glyphosate spray and fertilizer treatments. Fertilizer in all cases was 150 kg/ha Cropmaster 20 (NPKS = 19%, 10%, 0%, 16%).

1.1 Monitoring aeolian sediment transport

Reliable and accurate measurement of soil loss by the wind is difficult but essential for informed land management decision-making. Soil loss by wind erosion in the degraded tussock grasslands of Central Otago is most frequent during spring foehn northwesterly winds (McGowan *et al.* 1996). These produce elevated temperatures in the study area and extremely low relative humidity (<10%). Wind speeds during foehn events commonly exceed 20 $m \cdot s^{-1}$ to 30 $m \cdot s^{-1}$, well above widely published threshold entrainment velocities of 6 $m \cdot s^{-1}$ to 8 $m \cdot s^{-1}$ for wind erodible surfaces (Pye 1987). Sediment traps deployed in the field have to be robust, reliable and efficient collectors of wind-blown sediment over a wide range of wind speeds. Two sediment trap designs (for saltation/soil creep and suspension) were selected to monitor the principal modes of grain transport. Dust deposition traps were also deployed to monitor background dust input from wet and dry deposition. All traps were installed inside and outside the trial area to compare the effect of different drilled treatments on wind erosion with that of the surrounding degraded tussock grasslands.

Saltation and soil creep were monitored using modified Guelph-Trent Wedge (GTW-traps; Nickling and McKenna 1997; Figure 1). These passive vertical depth-integrated samplers are mounted on a base buried in the soil to a depth of 240 mm. The traps are fitted with a large wind vane and rotate freely so that they align into the prevailing wind. The base of the air inlet (500 mm high and 20 mm wide) is positioned flush with the ground surface. Particles filtered from the airstream are collected in a detachable sample jar housed within the trap base. The trap is constructed entirely of stainless steel including the 200 mesh filter.

Fig.1 Guelph-trent wedge saltation trap

Nickling and McKenna (1997) concluded that GTW-traps present minimal disturbance to airflow over a wide range of wind speeds, while maintaining a very high sampling efficiency. This results from the venturi-based venting of air through the wedge-shaped trap, which allows near isokinetic sampling (Nickling and McKenna 1997). These traps were allowed to bed-in before sampling commenced to ensure data were not affected by sediment disturbed during the installation of the traps. Initially two, but now four of these traps have been installed. One is outside the trial, the others inside with two in drilled/seeded plots (*Dorycnium* and *Dactylis*) and one in a sprayed/drilled plot.

Dust transport into and from the trials by suspension was monitored with a network of Fryrear traps (Fryrear 1986; Figure 2) modified to include a rain hood (Shao *et al.,* 1993). These passive single point traps, also constructed from stainless steel, are ideally suited to applications involving long exposure periods and can be considered to have near isokinetic sampling characteristics (Shao *et al.,* 1993). Three Fryrear traps were mounted on a mast at 0.5 m, 1.2 m and 4m above the soil surface. Laboratory tests indicate that these traps are approximately 90% efficient, although this declines with height especially for clay size particles (<2 um). Two Fryrear masts were placed on-site, one inside and the other some 50 m outside the trial.

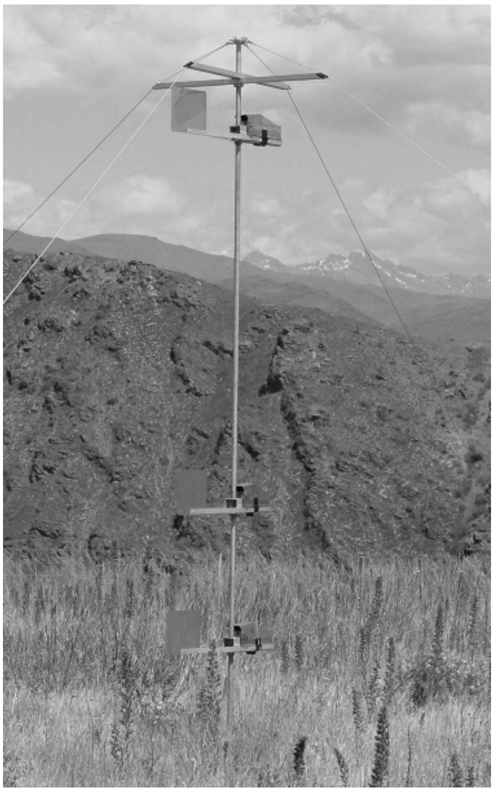


Fig.2 Fryrear Suspension Trap

Dust deposition was monitored using inverted frisbee traps (Figure 3) based on the plans of Hall *et al.* (1994). Each trap consists of a vertically facing open bowl centrally mounted to a collection tube which has a sample flask screwed to its base. The traps have a depth to width ratio of 0.2 causing minimal aerodynamic blockage resulting in a very efficient deposition gauge (Vallack 1995). The traps are positioned at least 1 m above the ground to prevent contamination by local saltating material and are constructed from aluminium. An open cell foam pad is placed in the bottom of each trap to reduce re-suspension of dust and to eliminate loss by rain splash. Two deposition traps were placed on site, one inside and the other outside the trial.

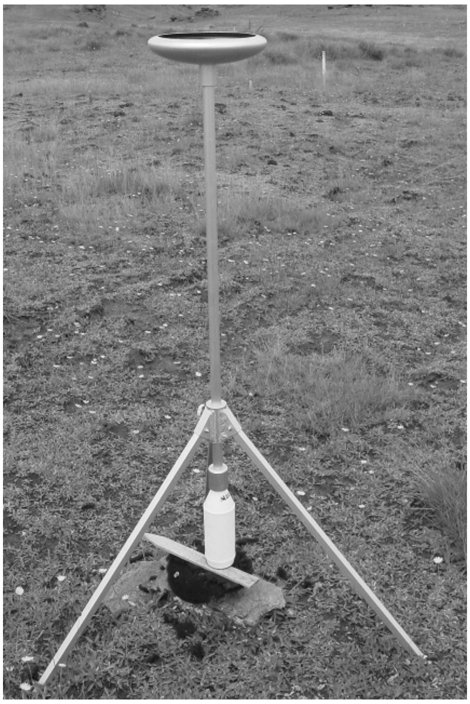


Fig.3 Hall (Frisbee) Deposition Trap

1.2 Data recording

A meteorological station was installed within the trial area in September 1999 along with the sediment traps both inside and outside the trial. A comprehensive database of climatic parameters was recorded, including temperature, relative humidity and wind run at 1m and 3m heights, plus solar radiation, wind direction, atmospheric pressure, precipitation and soil temperature at 15min intervals. The climate data logger and saltation traps were serviced monthly, the Fryrear and deposition traps bi-monthly. Wind direction and wind run were split into quarterly periods. Soil water to 10 cm depth was measured monthly by gravimetric means.

Sediment trap samples were washed into pre-weighed beakers, dried at 40℃ for 12 hours and weighed to determine total sample mass. Hydrogen peroxide digestion was then carried out in a hot water bath for a minimum of 5 days: samples were rinsed, settled, dried and reweighed to determine the proportionate masses of mineral and organic matter.

Vegetation changes were evaluated using permanently marked transects set up outside and within each trial plot (2m × 10m), and point-analysed at 0.25m intervals. These were assessed in November 2000 and April 2001. Total accumulated biomass levels (dry matter yield) were measured pre- and post-summer using 1m² quadrats. Regrowth from the spring cut was also determined in autumn. Root biomass (5cm × 5cm × 10cm plugs) was determined in August and December 2000, and May 2001, for both drilled and resident species, and the root diameter range was measured for the drilled species. Soil testing (New Zealand “Quicktest” analysis; Cornforth and Sinclair 1984) was conducted after establishment in Jan 1999 and again in May 2001.

2 Results

Soil: The results of soil nutrient testing were as follows:

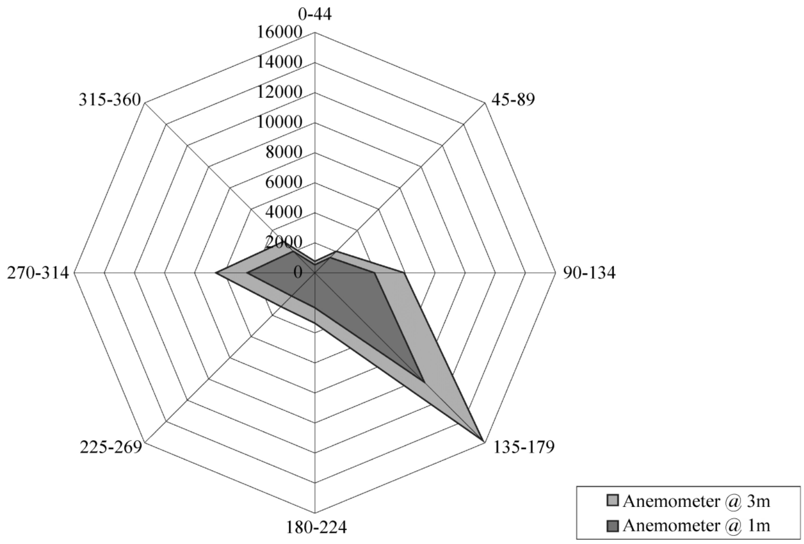
Table 1 Soil nutrient status – Waenga site

Sample	pH	P	K	Ca	Mg	S	Na
1999—Fertiliser	6.7	10	13	8	22	1	2
2001—Fertiliser	6.5	6	9	5	15	1	2
1999 + Fertiliser	6.3	27	14	7	21	8	3
2001 + Fertiliser	6.2	10	9	4	13	1	2

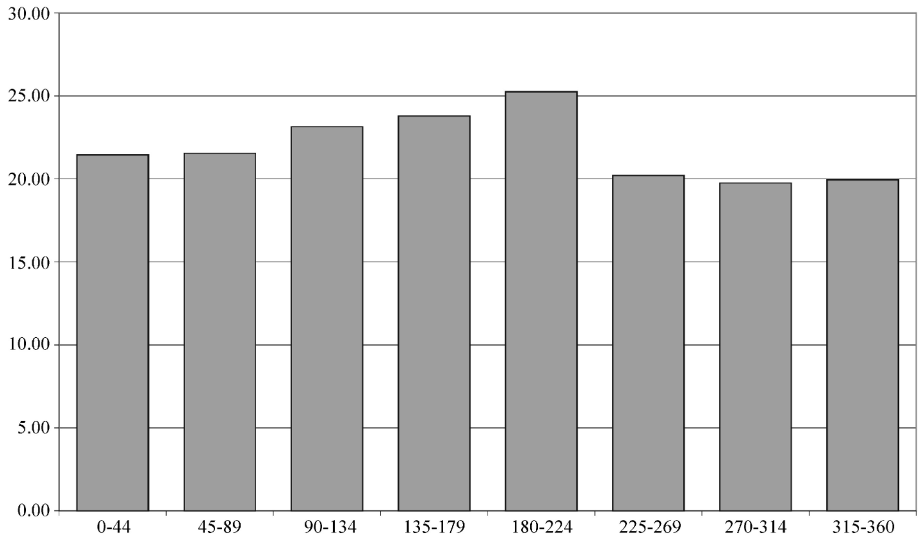
In little over 1.5 years apparent nutrient losses were significant, with P levels less than half what they were shortly after establishment and S levels back to base levels. pH levels have remained relatively stable. Soil water levels ranged from a winter (July-September) high of about 20% (w/w) to a summer (January-April) low of about 5%.

2.1 Climate

Total rainfall for the duration of the trial was 285 mm, most of which fell in October and January when 70+ mm monthly totals were recorded. Meteorological data associated with wind speed and direction are most pertinent to local sediment movement and erosion processes. Wind speed data for the period October 2000 to end December is presented in Fig 4. Data for the other periods was similar. Accumulated wind speed (radial graph) and maximum wind speed (bar graph) are shown by 45° compass sectors. Wind direction correlated closely with the data for accumulated wind speed, i.e. for October-December the wind was predominantly from the SW direction, with lesser influence from the W. The latter period was windier than July-September or January-February. Accumulated wind speeds for the anemometer at 1m were generally about 75% of those recorded at 3m.



A.Total wind velocity for period(m)



B.Maximum wind speed (m/sec)

Fig.4 Sum and maximum wind speed by direction, October 2000 to December 2000 at 1m and 3m above ground in Central Otago, New Zealand.

For the maximum wind speeds, in July-September the highest wind speeds (~25 m/sec) were recorded from the NE, the SE and the NW directions. During October-December the highest wind speed was recorded from the S and SE, and for January-February from the SE in general.

2.2 Aeolian sediment capture

Sediment entrainment levels above ground level (Fryrear traps) were low. Little difference was noted between the traps at different heights, or inside vs. outside the trial. Levels averaged 0.2 g—0.3 g perlinear metreper day over summer, being lower during winter. Organic matter levels increased during summer, peaking in autumn. Background deposition (deposition traps) rates were variable but low (0.1 kg • ha • day^{-1}—0.3 kg • ha • day^{-1}) and uniform inside and outside the trial.

The lowest sediment yield for the saltation traps (0.2 g • lm^{-1} • day^{-1}—0.5 g • lm^{-1} • day^{-1}) occurred within the establishing drilled/seeded plots (especially *Dorycnium* in February, Table 2). *Dactylis* produced higher sediment yields than *Dorycnium* except for the December/January period when they were similar. The trap outside the trial area also had low yields during the investigation period.

Sediment movement in the bare sprayed/drilled plot was 2—4 times that of adjacent drilled plots. The average mass ranged from 1 g—2 g per linear metre per day. Levels of organic matter in the samples peaked over mid-summer when plants were flowering (pollen and windblown seed were significant contributors) and insects were most active.

2.3 Plant cover and productivity

Groundcover during spring varied from 21% bare ground (sprayed plots) to 1%—5% bare ground for most other plots (and outside the trial). The balance of groundcover in the sprayed plots consisted of litter and annual weeds. High litter levels (20%—30%) were recorded for the control and resident + fertilizer plots, and for the area outside the trial. Of the drilled species, *Dactylis* produced a high level of cover (39%) but its accumulated biomass (1.3 tDM/ha) was lower than that of the more erect *Arrhenatherum* (28%; 19 tDM/ha). *Dactylis* plots contained fewer plants per m^2 with spreading foliage, less resident vegetation and more bare ground.

By autumn 2001 the extent of bare ground in the sprayed plots had increased to 33% and that outside the trial doubled to 8%. Other plots remained similar to spring. Litter levels were higher for all plots, including the area outside the trial, as a result of dry summer conditions. For the drilled species, *Dactylis* maintained the highest groundcover (49%) at the expense of resident species. *Arrhenatherum* (34%) and *Lotus* (34%) were next in terms of groundcover, followed by *Dorycnium* (28%). *Dorycnium* produced the greatest accumulated biomass (1.5 t/ha) and also provided the best spring-autumn regrowth (0.6 t/ha).

In August 2000 *Arrhenatherum* recorded the greatest root biomass (3.8 g/d^3). By December its root biomass was superceded by that of *Thinopyron* (7.6 g/d^3 vs 4.8 g/d^3), the plant with the lowest foliar biomass. By May 2001 *Thinopyron* root biomass had increased to 14 g/d^3, nearly double that of *Arrhenatherum*. *Dorycnium* recorded the lowest root biomass by May (3.2 g/d^3) but the diameter of its large roots showed a substantial increase from December to May.

3 Discussion

A combination of sediment monitoring techniques was used to determine the extent of wind erosion at a low altitude, exposed South Island site, comparing drilled and non-drilled treatments. The rate of sediment entrainment above ground level and background deposition both inside and outside the trial area was low and relatively uniform across the site. The low background deposition rate, for example, compared with an actively eroding site near Lake Tekapo ranging from 70 kg • ha^{-1} • month^{-1}—500 kg • ha^{-1} • month^{-1} (H. McGowan pers. com.). The equipment used proved robust and reliable and few technical problems were experienced.

Movement of sediment by saltation in the “worst-case scenario” sprayed plots was consistently higher than that of the vegetated plots and the area outside by up to 4 times. Within the two sampled drilled/seeded plots sediment movement was low. Levels in the *Dactylis* plots were 2-5 times higher than *Dorycnium* except for two months (December and January) when levels were similar. Vegetation cover measurement showed that although *Dactylis* had a good foliage canopy, it often had fewer plants per m^2, more bare ground occurred at its base and less resident vegetation was associated with it than other species in this trial. Low sediment levels were recorded outside the trial area which resulted from exceptional spring growth of *Echium vulgare* (vipers bugloss), the presence of much litter in autumn and low rabbit numbers following the introduction of Rabbit Haemorrhagic Disease in 1998.

Soil fertility levels dropped quickly via a combination of factors: plant uptake, immobilization, leaching and possibly erosion, this having long-term implications for plant growth. The meteorological comparison shows that the past decade and a half has generally been wetter than the long-term (1949—1980) mean; air temperatures varied little but the grass minimum was higher and fewer frost days occurred; and relative humidity was slightly higher.

Wind direction was mainly from a southerly direction during the investigation period, contrasting with the strong north-westerlies experienced during the previous “El Nino”-influenced drought period (1999/2000). Wind speed maxima from all directions exceeded commonly accepted threshold entrainment wind velocities 3—4 fold during this study, thus the potential for wind erosion on dry, unprotected soils is high. Threshold entrainment wind velocities have not yet been determined for this particular site/soil type. With wetter climatic conditions and fewer dry foehn winds during the reported period, it is likely the level of wind erosion measured was lower than might be expected. No major storm events occurred during the study period and severe drought as experienced in 1998/99 or a recovery of the rabbit population could result in a marked reversal of these results.

Increased soil nutrient levels did provide adequate, if temporary, resident ground cover but it contained few plants with grazing value and deteriorated quickly during summer drought, leaving large quantities of litter by autumn 2001. *Arrhenatherum* and *Dactylis* provided the greatest biomass and groundcover of the drilled species during spring 2000 but *Dorycnium* had the highest biomass by autumn 2001. It also had the best regrowth and this is reflected in the lower sedimentation rates that resulted.

Development of underground root systems is important in terms of a plant’s ability to stabilize the soil. *Arrhenatherum* had the greatest root biomass in spring, reflecting the early growth of this plant. As summer progressed the plant with the lowest foliar biomass, *Thinopyron,* nearly doubled its root biomass compared to that of *Arrhenatherum*. This is consistent with the former’s production of a comprehensive rhizomatous root system well in advance of foliage growth (Wills *et al.*, 1998). *Dorycnium* had the lowest root biomass in the surface 10 cm. However the shallow sampling depth may not reflect true root production by this shrub which has few surface feeder roots and a deeply penetrating tap root (Wills *et al.*, 1999).

The use of well-established plants that exhibit good ground cover and a comprehensive soil-binding root system is essential to minimize sediment movement in dry climate soils. In semi-arid environments, management strategies incorporating perennial drought-tolerant forage plants together with extended establishment periods should provide better protection against wind erosion than resident pasture, providing they can be established effectively.

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Table 2 Weight and composition of surface sediment sampled with Guelph-Trent Wedge traps on a monthly basis from June 2000 to February 2001 in Central Otago, New Zealand for an argillic semi-arid soil

Saltation Traps	Days in Sample	Date Sample Taken	.																
Sample Weights	33	**4-Jul-00**	26	**31-Jul-00**	30	**31-Aug-00**	33	**3-Oct-00**	24	**27-Oct-00**	37	**4-Dec-00**	25	**29-Dec-00**	32	**1-Feb-01**	26	**27-Feb-01**	
		Wt (gm)		**Wt (gm)**		**Wt (gm)**		**Wt (gm)**		**Wt (gm)**		**Wt (gm)**		**Wt (gm)**		**Wt (gm)**		**Wt (gm)**	
Trap 1 (Dactylis glomerata)						New traps installed >>		**0.97**		**0.33**		**0.18**		**0.16**		**0.29**		**0.44**	
Trap 2 (Dorycnium hirsutum)						New traps installed >>		**0.09**		**0.15**		**0.09**		**0.20**		**0.33**		**0.09**	
Trap 3 (Sprayed)		**0.10**		**0.32**		**0.65**		**1.44**		**0.63**		**0.39**		**1.11**		**0.76**		**0.28**	
Trap 4 (Outside)		**0.10**		**0.07**		**0.10**		**0.29**		**0.10**		**0.13**		**0.12**		**0.24**		**0.10**	
Composition (Organic/Mineral)		**% Org**	**% Min**	**% Org**	**% Min**	**% Org**	**% Min**	**% Org**	**% Min**	**% Org**	**% Min**	**% Org**	**% Min**	**% Org**	**% Min**	**% Org**	**% Min**	**% Org**	**% Min**
Trap 1 (Dactylis glomerata)								**4**	**96**	**6**	**94**	**28**	**72**	**44**	**56**	**17**	**83**	**34**	**66**
Trap 2 (Dorycnium hirsutum)								**22**	**78**	**7**	**93**	**22**	**78**	**45**	**55**	**15**	**85**	**56**	**44**
Trap 3 (Sprayed)		**0**	**100**	**0**	**100**	**2**	**98**	**35**	**65**	**3**	**97**	**5**	**95**	**8**	**92**	**7**	**93**	**14**	**86**
Trap 4 (Outside)		**0**	**100**	**0**	**100**	**0**	**100**	**7**	**93**	**10**	**90**	**54**	**46**	**42**	**58**	**38**	**63**	**50**	**50**