Application of the Vetiver System for Phytoremediation of Mercury Pollution in the Lake and Yolo Counties, Northern California

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Abstract: The Vetiver System was first developed for soil and water conservation in farmlands. While this application still plays a vital role in agricultural lands, recent R&D have demonstrated that vetiver grass is also highly suitable for phytoremedial application due to some of its extraordinary features. These include a massive and deep root system, tolerance to extreme climatic variations such as prolonged drought, flood, submergence, fire, frost and heat waves. It is also tolerant to a wide range of soil acidity, alkalinity, salinity, sodicity, and elevated levels of Aluminium, Manganese, and heavy metals such as Arsenic, Cadmium, Chromium, Nickel, Lead, Zinc, Mercury, Selenium and Copper in the soil.

Successful rehabilitation of mine tailings and landfills with elevated levels of heavy metals in Australia, China and South Africa indicates that the Vetiver System should provide a powerful phytoremedial tool for the attenuation of the mercury pollution problem in Yolo and Lake Counties by trapping and containing both the air and water born insoluble mercury at sources, and by reducing the soluble fraction in acid mine drainage.

1 INTRODUCTION

Contamination of the environment by by-products of rural, industrial and mining industries is a major global concern. The majority of these contaminants are high levels of heavy metals which can affect flora, fauna and humans living in the areas, in the vicinity or downstream of the contaminated sites. Table 1 shows the maximum level of heavy metals tolerated by environmental and health authorities in Australia. Strict guidelines for methods of remediation or rehabilitation have been set out by authorities to prevent the spread of pollutants to the surrounding environment.

Common methods used to treat the contaminants such as chemical treatment with chelating agents, deep burial or removal from site are expensive, impractical and at times impossible to carry out, as the volume of contaminated materials is very large, examples are gold, coal mine and mercury tailings here in Lake County.

2 A STRONG CASE FOR PHYTOREMEDIATION

When the contaminated wastes cannot be practically or economically treated or removed, off-site pollution caused by the spreading of the pollutants must be prevented. Wind and water erosion and leaching are often the causes of off-site contamination. Literature shows that phytoremediation is the most practical and economical means of attenuating the problem on large scale. An effective erosion and sediment control program using vegetation to trap pollutants and rehabilitate the contaminated sites provides a more attractive alternative than chemical or mechanical treatments. However plant establishment on these sites is often very difficult and slow due to the hostile growing conditions including elevated levels of heavy metals, which are often toxic to plant growth. Plant species needed for phytoremedial works must be very hardy and resilient with high level of tolerance to elevated heavy metal concentrations as well as other adverse growing conditions.

3 SOME SPECIAL CHARACTERISTICS OF VETIVER GRASS SUITABLE FOR PHYTOREMEDIATION

Vetiver grass (*Vetiveria zizanioides L.*), due to its unique morphological and physiological characteristics, which has been widely known for its effectiveness in erosion and sediment control (10,20), has also been found to be highly tolerant to extreme soil conditions including heavy metal toxicities (18).

Table 1 Investigation thresholds for contaminants in soils (Ref.2)

Heavy Metals	Thresholds ($mgKg^{-1}$)	
	Environmental *	Health *
Antimony (Sb)	20	-
Arsenic (As)	20	100
Cadmium (Cd)	3	20
Chromium (Cr)	50	-
Copper (Cu)	60	-
Lead (Pb)	300	300
Manganese (Mn)	500	-
Mercury (Hg)	1	-
Nickel (Ni)	60	-
Tin (Sn)	50	-
Zinc (Zn)	200	-

*Maximum levels permitted, above which investigations are required.

3.1 Tolerance to Adverse Conditions (21)

- Tolerance to extreme climatic variation such as prolonged drought, flood, submergence and extreme temperature from -22°C to 60°C.
- Ability to regrow very quickly after being affected by drought, frost, salinity and other adverse soil conditions after the weather improves or soil ameliorants added
- Tolerance to wide range of soil pH (3.0 to 10.5).
- Highly tolerant to growing medium high in acidity, alkalinity, salinity, sodicity and magnesium.

3.2 Tolerance to Elevated Heavy Metals Concentrations (21)

- Highly efficient in absorbing dissolved nutrients and heavy metals in polluted water.
- Highly tolerant to Al, Mn and heavy metals such as As, Cd, Cr, Ni, Pb, Hg, Se and Zn in the soils.

A summary of the above characteristics is presented in Appendix 1 and data on the effects of heavy metals on vetiver growth are shown in Appendix 2.

3.3 Stiff and Erect Stems Forming Dense Hedges (21)

- Stiff and erect stems, which can stand up to relatively deep water flow.
- A dense hedge is formed acting as sediment filter and water spreader.
- New shoots emerge from the base helping it to withstanding heavy traffic and heavy grazing pressure.
- Vetiver grass has no stolons and a massive finely structured root system that can grow very fast. This deep root system makes vetiver plant extremely drought tolerant and difficult to dislodge by strong current.
- Vetiver is sterile and non-invasive.
- Highly resistance to pests, diseases and fire.
- New shoots develop from the underground crown therefore protecting them from fire and frost
- New roots are developed from nodes when buried by trapped sediment.

Table 2 Tolerance range of vetiver grass

Adverse Soil Conditions	Levels (Available)
Acidity	pH 3.0
Aluminium level (Al Sat. %)	Between 80% - 87%
Manganese level	> 578 $mgkg^{-1}$
Alkalinity (highly sodic)	pH 11
Salinity (50% yield reduction)	17.5 $mScm^{-1}$
Salinity (survived)	47.5 $mScm^{-1}$
Sodicity	48% (exchange Na)
Magnesicity	2 400 $mgkg^{-1}$ (Mg)
Heavy Metals	
Arsenic	100 - 250 $mgkg^{-1}$
Cadmium	22 $mgkg^{-1}$
Copper	174$mgkg^{-1}$
Chromium	200 - 600 $mgkg^{-1}$
Nickel	50 - 100 $mgkg^{-1}$
Mercury	> 6 $mgkg^{-1}$
Lead	>1500 $mgkg^{-1}$ (3123)*
Selenium	> 74 $mgkg^{-1}$
Zinc	>750$mgkg^{-1}$ (3418)*

* Total content

3.4 Tolerant to Cold Weather (21)

Although vetiver is a tropical grass, it can survive and thrive under extremely cold conditions. Under frosty weather its top growth is killed but its underground growing points survived. In Australia, vetiver growth was not affected by severe frost at –11^{o}C (12 ^{o}F) and it survived for a short period at –22 ^{o}C (7.6 ^{o}F) in northern China (33).

Recent research showed that 25^{o}C (72^{o}F) was optimal soil temperature for root growth, but vetiver roots continued to grow at 13^{o}C (55^{o}F). Although very little shoot growth occurred at the soil temperature range of 15 ^{o}C (day) and 13 ^{o}C (night) root growth continued at the rate of 126 mm/day (5in.), indicating that vetiver grass was not dormant at this temperature (29) and extrapolation suggested that root dormancy occurred at about 5 ^{o}C (41^{o}F).

3.5 Vetiver Grass Growth in Yolo County

Yolo County has a relatively mild winter and warm summer. As vetiver roots continued to grow at soil temperature of 55 ^{o}F (27), it is expected that vetiver will start growing by late March when minimum soil temperature is around 56 ^{o}F and continue until early November, when soil moisture permitted.

Vetiver produced on average 200 tillers after two years and up to 6 feet tall, with best growth occurs at ambient temperature of about 70 ^{o}F. Vetiver grass survived –8^{o}C (17 ^{o}F) for 10 consecutive days in the early 1990s. The plants were frost burnt to the ground but rebounded vigorously in spring (J. Eagan pers. com.).

4 WHY VETIVER SYSTEM?

The above features shows that vetiver grass is rather unique; it has the ability to control erosion and sedimentation, to withstand extremely soil and climatic variations and to tolerate elevated heavy metals concentrations in water and soil. Vetiver is sterile and non-evasive, it does not compete with native vegetation and as a nurse plant it fosters the voluntary return of native plants.

But most importantly, VS is proven technology, its effectiveness as an environmental protection tool has been demonstrated around the world and some parts of the US (12,20,21). The attendance of over 300 delegates from 40 countries at the recent International Vetiver Conference: ***VETIVER AND THE ENVIRONMENT*** in Thailand is a strong testimony to this effect.

There exist plants with similar morphological characteristics as, vetiver but their tolerance to adverse conditions and heavy metal toxicities are not known. VS offers a ready made solution to a pressing problem of Hg pollution in this region.

The followings are R&D results, which show the wide-ranging tolerance of vetiver grass to adverse conditions and heavy metal toxicities, and also field applications in Australia, China and South Africa where VS has been highly effective in the rehabilitation of contaminated mine tailings and agrochemicals. All the researches and applications in Australia reported in this paper were conducted using the Monto genotype (registered in Australia as Monto vetiver), but DNA typing has shown that Monto is genetically identical to the sterile Sunshine genotype in the US (1). Therefore the following results can be applied with confidence when the sterile Sunshine genotype is used for phytoremediation in California.

5 TOLERANCE OF VETIVER GRASS TO ADVERSE SOIL CONDITIONS

5.1 Tolerance to High Acidity, and Manganese and Aluminium Toxicities

Results from glasshouse studies show that when adequately supplied with nitrogen and phosphorus fertilisers, vetiver can grow in soils with very high level of acidity, aluminium and manganese.

Vetiver growth was not affected and no obvious symptoms were observed when soil pH as low as 3.3 and the extractable manganese reached 578 $mgKg^{-1}$, and plant manganese was as high as 890 $mgKg^{-1}$. Bermuda grass (*Cynodon dactylon*) which has been recommended as a suitable species for acid mine rehabilitation, has 314 $mgKg^{-1}$ of manganese in plant tops when growing in mine wastes containing 106 $mgKg^{-1}$ of manganese (16).

Vetiver also produced excellent growth at a very high level of soil aluminium saturation percentage (68%), but it did not survive an aluminium saturation level of 90% at soil pH of 2.0. Although a critical level of aluminium could not be established in this trial, observation during the trial indicated that the toxic level for vetiver would be between 68% and 90% (17). These results are supported by recent works in Vanuatu where vetiver has been observed to thrive on highly acidic soil with aluminium saturation percentage as high as 87% (Miller pers.com.).

5.2 Tolerance to Acid Sulfate Soils.

Acid Sulfate Soils (ASS) are highly erodible and difficult to stabilise and rehabilitate due to its extremely acidic conditions, with pH between 3 and 4. Eroded sediment and leachate from ASS are also extremely acidic. The leachate from ASS has led to disease and death of fish in several coastal zones of eastern Australia. Vetiver has been successfully used to stabilise and rehabilitate highly erodible ASS on the coastal plain in tropical Australia, where actual soil pH is around 3.5 and oxidised pH is as low as 2.8 (17).

6 TOLERANCE TO HEAVY METALS

6.1 Tolerance Levels in Soil and Water

A series of glasshouse trials was carried out to determine the tolerance of vetiver to high soil levels of heavy metals. Literature search indicated that most vascular plants are highly sensitive to heavy metal toxicity and most plants were also reported to have very low threshold levels for arsenic, cadmium, chromium, copper and nickel in the soil. Results shown in Table 3 demonstrate that vetiver is highly tolerant to these heavy metals. Appendix 2 shows the effect of heavy metal concentration in the soil on vetiver growth.

Research on wastewater treatment in Thailand found that vetiver grass could absorb substantial quantity of Pb, Hg, Cd in waste water (14).

Table 3 Threshold levels of heavy metals to vetiver growth as compared with other plants

Heavy Metals	Thresholds to Plant Growth ($mgKg^{-1}$)		Thresholds to Vetiver Growth ($mgKg^{-1}$)	
	Hydroponic (4)	Soil levels (3)	Soil levels	Shoot levels
Arsenic	0.02-7.5	2.0	100-250	21-72
Cadmium	0.2-9.0	1.5	20-60	45-48
Copper	0.5-8.0	NA	50-100	13-15
Chromium	0.5-10.0	NA	200-600	5-18
Lead	NA	NA	>1 500	>78
Mercury	NA	NA	>6	>0.12
Nickel	0.5-2.0	7-10	100	347
Selenium	NA	2-14	>74	>11
Zinc	NA	NA	>750	>880

NA Not available

6.2 Shoot Contents of Heavy Metals

Vetiver can also tolerate very high concentration heavy metals in plant shoots, for arsenic, the toxic content for most plants is between 1 and 10 $mgKg^{-1}$, for vetiver the threshold level is between 21 and 72 $mgKg^{-1}$. Similarly for cadmium, the toxic threshold for vetiver is 45 $mgkg^{-1}$ and for other plants between 5 and 20 $mgkg^{-1}$. An impressive finding was that while the toxic thresholds of vetiver for chromium is between 5 and 18 $mgkg^{-1}$ and that for nickel is 347 $mgKg^{-1}$, growth of most plants is affected at the content between 0.02 and 0.20 $mgKg^{-1}$ for chromium and between 10 and 30 $mgKg^{-1}$ for nickel. Vetiver had similar tolerance to copper as other plants at 15 $mgKg^{-1}$ (3,4,6,8).

6.3 Tolerance to Mercury

Higher level of Hg than 6 $mgKg^{-1}$ was not used in the study reported above because it was selected to represent 6 times higher than the level the current contaminated land threshold allowed in Australia (Table 1). Therefore the full potential of Hg tolerance of vetiver grass has not assessed but as in the cases with other heavy metals, it can reasonably be expected that vetiver can tolerate Hg at a much higher level in the soil than 6 $mgKg^{-1}$ as indicated above.

6.4 Distribution of Heavy Metals in Vetiver Plant

Data in Appendix 3 show that the distribution of heavy metals in vetiver plant can be divided into three groups:

- very little of the arsenic, cadmium, chromium and mercury absorbed were translocated to the shoots (1% to 5%),
- a moderate proportion of copper, lead, nickel and selenium were translocated (16% to 33%) and
- zinc was almost evenly distributed between shoot and root (40%)

The important implications of these findings are that when vetiver is used for phytoremediation of sites contaminated with high levels of arsenic, cadmium, chromium and mercury, its shoots can be safely grazed by animals or harvested for mulch as very little of these heavy metals are translocated to the shoots. Similarly in the case of wildfire, very little mercury will pollute the air. As for copper, lead, nickel, selenium and zinc their uses for the above purposes are limited to the thresholds set by the environmental agencies and the tolerance of the animal concerned.

In addition, although vetiver is not a hyper-accumulator it can be used to remove the some heavy metals from the contaminated sites and disposed off safely elsewhere, thus gradually reducing the contaminant levels. For example vetiver roots and shoots can accumulate more than 5 times the chromium and zinc levels in the soil and almost twice for mercury (Appendix 2). In the case of mercury, vetiver absorbed more Hg from the soil than alfalfa, when Hg in the soil was at 97 $mgKg^{-1}$, Hg concentration of alfalfa roots was 9.8$mgKg^{-1}$ (9), with vetiver the root concentration was at 10.8 $mgKg^{-1}$ when the soil Hg level was at 6.1 $mgKg^{-1}$.

7 AN EFFECTIVE FILTER (21)

When planted as contour hedge vetiver grass forms a porous barrier, slows and spreads runoff water, and filters both fine and coarse sediment. Table 4 shows vetiver hedges trapped almost 100% of solids from clay contaminated storm water during peak flow at a bentonite mine site.

Table 4 Time taken for 300mL of water to pass through a 2 mm sieve.

Water samples	Time
Upstream from Row	20.54 sec
Downstream from Row	11.76 sec
Distilled Water	11.20 sec

8 REHABILITATION OF MINE TAILINGS IN AUSTRALIA (19)

8.1 Gold Mines

The environment of both fresh and old gold tailings is highly hostile to plant growth. The fresh tailings are typically alkaline (pH = 8-9), low in plant nutrients and very high in free sulphate (830 $mgKg^{-1}$), sodium and total sulfur (1-4%). Vetiver established and grew very well on these tailings without fertilisers, but growth was improved by the application of 500 $Kgha^{-1}$of Di-ammonium Phosphate.

Due to its high sulfur content, old gold tailings are often extremely acidic (pH 2.5-3.5), high in heavy metals and low in plant nutrients. Table 5 shows a common heavy metal profile of gold tailings in Australia. At these levels some of these metals are toxic to plant growth and also exceed the environmental investigation thresholds set out in Table 1. Revegetation of these tailings is very difficult and often very expensive and the bare soil surface is highly erodible. These tailings are often the source of contaminants, both above ground and underground to the local environment.

When adequately supplied with nitrogen and phosphorus fertilisers, excellent growth of vetiver was obtained on sites with pH ranging from 2.7 to 3.6, high in sulphate (0.37%-0.85%), total sulfur (1.31%-3.75%) and low in plant nutrients. Liming was not needed on sites with higher pH (3.5) but the addition of $20 tha^{-1}$ of agricultural lime significantly improved vetiver growth on site with pH=2.7.

Table 5 Heavy metal contents of typical gold mine tailings in Australia

Heavy Metals	Total Contents ($mgKg^{-1}$)	Threshold levels by EPA ($mgKg^{-1}$)
Arsenic	1 120	20
Chromium	55	50
Copper	156	60
Manganese	2 000	500
Lead	353	300
Strontium	335	NA
Zinc	283	200

NA Not available

8.2 Other Mines

Vetiver grass has also been successfully used to rehabilitate coal mine tailings which was saline, highly sodic, high levels of soluble sulfur, magnesium and calcium and extremely low in nitrogen and phosphorus. Plant available copper, zinc, magnesium and iron were also high (11).

Bentonite tailings are extremely erodible as they are highly sodic with Exchangeable Sodium Percentage (ESP) values ranging from 35% to 48%, high in sulphate and extremely low in plant nutrients. Vetiver established readily on these tailings and effectively controlled erosion, conserved moisture and improved seedbed conditions for the establishment of indigenous species.

Residue of bauxite processing known as Red Mud is highly caustic with pH level as high as 12. Vetiver established successfully on the Red Mud when its pH was raised to 9.0.

9 REHABILITATION OF MINE TAILINGS IN SOUTH AFRICA AND CHINA

Rehabilitation trials conducted by De Beers on slimes dams at several sites, have found that vetiver possessing the necessary attributes for self sustainable growth on kimberlite spoils. Vetiver grew vigorously on the alkaline kimberlite, containing run off, arresting erosion and creating an ideal micro-habitat for the establishment of indigenous grass species (7). Vetiver has also been used successfully in the rehabilitation diamond mines at Premier and Koffiefonteine and slimes dams at the Anglo American platinum mine at Rastenburg and the Velkom, President Brand gold mine (Tantum pers.com.).

In China vetiver produced biomass more than twice that of *Paspalum notatum, Cynodon dactylon* and *Imperata cylindrica* in the rehabilitation of the Lechang Pb and Zn mine, where tailings contain very high levels of heavy metals (Pb at 3 231 $mgKg^{-1}$, Zn at 3 418 $mgKg^{-1}$, Cu at 174 $mgKg^{-1}$ and Cd at 22 $mgKg^{-1}$)(13).

10 POTENTIAL REMEDIAL SOLUTIONS FOR MERCURY POLLUTION IN LAKE COUNTY

10.1 Sources of Hg

The University of California, Davis, Interim Final Report (15) prepared for the USEPA Superfund Program identified the Sulphur Bank Mercury mine is the primary point source of inorganic Hg contaminating Clear Lake. The Hg load derives primarily from the inorganic, highly insoluble, sulfur bound Hg in the un-reactive cinnabar form and secondly from the inorganic and soluble Hg pool associated with acidic mine drainage. The insoluble fraction derived from the erosion of Hg contaminated waste rocks and tailings piles and the soluble fraction from the reaction between the acidic leachate and the underground Hg body.

Contribution of the two Hg sources probably varies with the location of the mines, its history of disturbance and Hg concentration in the ore body. For the Sulphur Bank Mercury mine, it has been estimated that the insoluble fraction contributed 100 kg/year and the soluble fraction 100-400kg/year of Hg to Clear Lake and the latter was responsible for the production of flocculent material in the lake.

10.2 Remedial recommendations

The followings are some major recommendations of above report:

- Expand of the mine to include the wetland in the north
- Develop plan to reduce the flow of acid mine drainage from the mine to the lake at all time
- Prevent as much as possible rain water flow over/through the waste rock piles enroute to the lake
- Prevent the Herman Pit overflows (resulted from heavy rains and flood) from passing over/through the waste rock piles enroute to the lake.

10.3 Potential remedial solutions and recommendations

The report presented eight remedial options for lakebed sediment and 11 for acid mine drainage. The report recommended two remediation strategies, one dealing with lakebed sediment containing both organic and inorganic Hg and the other addressing the ongoing input of acid mine drainage from the mine.

While some of these options are purely academic, others are very costly and impractical to implement without causing further potential damage to the environment. Phytoremedial methods for runoff control and revegetation of waste rock and mine tailings piles offer a more effective, economical and environmental friendly option.

11 REMEDIAL SOLUTIONS USING THE VETIVER SYSTEM

Based on the recommendations of the above report, VS can provide an effective control of the ongoing input of Hg from the mine and hot springs to Clear Lake. Attenuation of both the highly insoluble, sulfur bound Hg form and the soluble Hg pool associated with acidic mine drainage is highly achievable.

The overall strategy is to:

- contain the Hg sources on site
- trap Hg laden silt as close to sources as possible.
- decontaminate the soluble fraction of Hg in artificial wetlands

11.1 Retaining the insoluble particulate Hg fraction

11.1.1 Containment of Hg at sources

The vetiver technology used for erosion and sediment control, rock wastes stabilisation and mine tailings rehabilitation can be applied very effectively to attenuate the spreading of the insoluble Hg fraction down stream. Once the contaminated areas were identified vetiver contour hedges should be established for erosion and sediment control, and water conservation. Hedge spacing varies with land slope, soil type and rainfall. The inter- hedge areas if not already vegetated should be planted with suitable species to provide surface cover. On 'hot' sites, due either to high contamination, unstable slopes, steep gradient or other adverse conditions, where establishment of other species is difficult, vetiver should be planted in the inter-row area as well. Layout of the hedges should allow for diversion of runoff water into strategically locate drainage lines where the Hg laden silt could be effectively trapped.

In addition to reducing water born pollutants, VS also provides an effective surface cover to prevent wind born Hg from spreading. In Australia vetiver hedges were planted to provide windbreak for dust storm suppression on gold mine tailings dams.

11.1.2 Trapping Hg silt close to source

Vetiver filter strips should be planted on all major and minor drainage lines and waterways to trap the Hg laden silt moving down slope.

11.2 Decontamination in Constructed Wetlands

For the soluble fraction of Hg in surface runoff and the fine particulate Hg from minor sources, artificial wetlands will offer a further step in reducing the Hg load reaching the lake. Application of wetlands as part of the phytoremediation measure is gaining momentum worldwide.

Wetlands involve a complex variety of biological process, including microbiological transformations and physio-chemical processes such as adsorption, precipitation or sedimentation. The ability of vetiver to tolerate flooded soil conditions and to absorb and decontaminate high levels of agrochemicals, heavy metals and nutrients makes it very suitable for use in ephemeral or permanent wetlands (5). Its dense stands of stiff, erect stems can reduce flow velocity, increase detention time and enhance deposition of sediment and sediment-bound contaminants. Furthermore, vetiver dense and finely structured root system can improve bed stability and nutrient uptake, and provide an environment that stimulates microbiological processes in the rhizosphere.

11.3 Reduction of the soluble Hg derived from acidic mine drainage

With its tolerance to highly acidic conditions and the extensive and very deep root system, vetiver can exploit the underground seepage during its summer growth, creating a negative pore pressure, which would provide a big reservoir for winter rain and ultimately reduce the volume of underground leachate. Vetiver has been used very successfully for this purpose in Australia to contain leachate runoff from landfills. For this application, high density planting is required at strategic locations such as the toes of major slopes of highly contaminated areas.

12 FUTURE R&D

A limited R&D program is needed to determine the threshold level of Hg on vetiver growth and management practices required to determine best establishment, promote early growth and maintenance procedures to ensure optimal results.

There is also a need to search/develop hyper-accumulator plants that can be used in conjunction with the Vetiver System to remove the Hg from the contaminated sites and disposed off safely elsewhere, thus gradually reducing the contaminant levels.

12 CONCLUSION

The vetiver system is proven technology, its effectiveness as an environmental protection tool has been demonstrated around the world. It is a very cost effective, environmental friendly and practical phytoremedial tool for the control and attenuation of heavy metal pollution when appropriately applied.

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Appendix 1

Adaptability Range of Vetiver in Australia and other Countries

Adverse Soil Conditions	Australia	Other Countries
Acidity	pH 3.0	pH 4.2 (with high level soluble aluminium)
Aluminium level (Al Sat. %)	Between 68% - 87%	80%-87%
Manganese level	> 578 $mgkg^{-1}$	
Alkalinity (highly sodic)	pH 9.5	pH 10.5
Salinity (50% yield reduction)	17.5 $mScm^{-1}$	
Salinity (survived)	47.5 $mScm^{-1}$	
Sodicity	48% (exchange Na)	
Magnesicity	2 400 $mgkg^{-1}$ (Mg)	
Heavy Metals		
Arsenic	100 - 250 $mgkg^{-1}$	
Cadmium	20 $mgkg^{-1}$	22 $mgkg^{-1}$
Copper	35 - 50 $mgkg^{-1}$	174 $mgkg^{-1}$
Chromium	200 - 600 $mgkg^{-1}$	
Nickel	50 - 100 $mgkg^{-1}$	
Mercury	> 6 $mgkg^{-1}$	
Lead	> 1 500 $mgkg^{-1}$	3 123 $mgkg^{-1}$
Selenium	> 74 $mgkg^{-1}$	
Zinc	>750 $mgkg^{-1}$	3 418 $mgkg^{-1}$
Latitude	15^0S - 37^0S	41^0N - 38^0S
Altitude		2 800m

Climate		
Annual Rainfall (mm)	450 - 4 000	250 - 5 000
Frost (ground temp.) (soil temperature)	-11^0C (12 °F)	-22^0C (7.6 °F) -10^0C (14 °F)
Heat wave	45^0C (113°F)	60^0C (140°F)
Drought (without effective rain)	15 months	
Fertiliser		
Vetiver can be established on very infertile soil	N and P (300 kg/ha DAP)	N and P, farm manure
Palatability	Dairy cows, cattle, horse, rabbits, sheep, kangaroo	Cows, cattle, goats, sheep, pigs, carp
Nutritional Value	N = 1.1 % P = 0.17% K = 2.2%	Crude protein 3.3% Crude fat 0.4% Crude fibre 7.1%

Appendix 2

Dry matter yield of vetiver as affected by various levels of As, Cd, Cu, Cr, Pb, Hg, Ni, Se and Zn in the soil

Heavy Metals	Soil Concentration ($mgKg^{-1}$)	Dry Matter Yield (g/pot)
Arsenic	20	43.85 a*
	100	43.51 a
	250	18.93 b
	500	5.56 c
	750	0 d
LSD (5%)		2.95
Cadmium	1	43.80 a*
	5	37.86 a
	10	34.08 a
	20	33.50 a
	60	21.06 b
	120	12.24 c
LSD (5%)		11.59
Copper	8	20.53 a*
	25	17.89 a
	50	18.87 a
	100	11.42 b
	150	4.58 c
	200	3.80 c
LSD (5%)		5.54
Chromium	10	35.29 a*
	50	28.71 a
	100	34.64 a
	200	25.80 a
	600	4.68 b
LSD (5%)		10.75
Lead	13	37.5
	91	35.0
	150	39.6
	330	36.9
	730	39.0

	1500	39.0	
LSD (5%)		n.s	
Mercury	0.02	37.9	
	0.36	43.8	
	0.64	42.0	
	1.22	46.8	
	3.47	37.7	
	6.17	40.4	
LSD (5%)		n.s	
Nickel	2	35.29	a*
	100	20.56	b
	200	3.21	c
	300	7.32	c
	400	1.31	c
	500	0.90	c
LSD (5%)		10.01	
Selenium	0.23	37.7	
	1.8	43.2	
	6.0	46.6	
	13.2	50.0	
	23.6	43.7	
	74.3	43.8	
LSD (5%)		n.s	
Zinc	9.5	37.5	
	150	38.6	
	180	42.7	
	220	43.5	
	230	40.0	
	240	35.3	
LSD (5%)		n.s	

*Different alphabets indicate significant difference
n.s. Non significant
BQ Below quantification

Appendix 3

Distribution of heavy metals in vetiver shoots and roots

Metals	Soil ($mgKg^{-1}$)	Shoot ($mgKg^{-1}$)	Root ($mgKg^{-1}$)	Shoot/ Root %	Shoot / Total %
Arsenic (As)	414	4.5	96	4.7	4.5
	605	6.5	124	5.2	5.0
	620	11.2	268	4.2	4.0
	844	10.4	228	4.6	4.4
	959	9.6	185	5.2	4.9
Average				4.8	4.6
Cadmium (Cd)	0.67	0.16	7.77	2.0	2.0
	0.58	0.13	13.60	1.0	0.9
	1.19	0.58	8.32	7.0	6.5
	1.66	0.31	14.20	2.2	2.1
Average				3.1	2.9
Copper (Cu)	50	13	68	19	16
Chromium (Cr)	50	4	404	1	1
	200	5	1170	<1	<1
	600	18	1750	1	1
Average				<1	<1
Lead (Pb)	13	0.5	5.1	10	9
	91	6.0	23.2	26	20
	150	13.2	29.3	45	31
	330	41.7	55.4	75	43
	730	78.2	87.8	87	47
	1500	72.3	74.5	97	49
Average				57	33
Mercury (Hg)	0.02	BQ	0.01	-	-
	0.36	0.02	0.39	5	5
	0.64	0.02	0.53	4	4
	1.22	0.02	0.29	7	6
	3.47	0.05	1.57	3	3
	6.17	0.12	10.80	11	6
Average				6	5
Nickel (Ni)	300	448	1040	43	30
Selenium (Se)	0.23	0.18	1.00	53	15
	1.8	0.58	1.60	36	27
	6.0	1.67	3.60	46	32
	13.2	4.53	6.50	70	41
	23.	8.40	12.70	66	40
	74.	11.30	24.80	46	44
Average				53	33
Zinc (Zn)	Control	123	325	38	27
	100	405	570	71	42
	250	520	490	106	51
	350	300	610	49	33
	500	540	830	65	39
	750	880	1030	85	46
Average				69	40

BQ: Below Quantification