

Leptospermum scoparium

now considered to be marginal for pastoral production due to high current erosion rates generated by shallow shrublands formerly considered a hindrance to pastoral farming can play an important role in mitigating erosion. *Leptospermum scoparium* (Forster et Forster) is a native New Zealand tree species that is widely distributed in the country. It is a member of the Myrtaceae family and is known for its ability to form dense, low-lying shrublands. These shrublands are often found in areas of marginal land where erosion susceptibility is high, and a tension exists between deriving economic gains

and improvements in stream health and water quality. The government-funded schemes, including the Afforestation Grant Scheme, have been instrumental in promoting the establishment of *Leptospermum scoparium* plantations. These plantations are often established in areas of marginal land where erosion susceptibility is high, and a tension exists between deriving economic gains and improvements in stream health and water quality. The government-funded schemes, including the Afforestation Grant Scheme, have been instrumental in promoting the establishment of *Leptospermum scoparium* plantations. These plantations are often established in areas of marginal land where erosion susceptibility is high, and a tension exists between deriving economic gains and improvements in stream health and water quality.

for its high-value honey and oil with unique anti-bacterial properties. The National Environmental Standards for Plantation Forestry (NES-PF) sets out the requirements for the establishment and management of plantation forests. The NES-PF requires that plantations be established in areas of marginal land where erosion susceptibility is high, and a tension exists between deriving economic gains and improvements in stream health and water quality. The government-funded schemes, including the Afforestation Grant Scheme, have been instrumental in promoting the establishment of *Leptospermum scoparium* plantations. These plantations are often established in areas of marginal land where erosion susceptibility is high, and a tension exists between deriving economic gains and improvements in stream health and water quality.

erosion control is afforded by these plantings. Much of the research relevant to understanding the

of storm effects (e.g., landslide prevention) by closed-canopied *Leptospermum scoparium* plantations. The research has shown that *Leptospermum scoparium* plantations can play an important role in mitigating erosion. The government-funded schemes, including the Afforestation Grant Scheme, have been instrumental in promoting the establishment of *Leptospermum scoparium* plantations. These plantations are often established in areas of marginal land where erosion susceptibility is high, and a tension exists between deriving economic gains and improvements in stream health and water quality. The government-funded schemes, including the Afforestation Grant Scheme, have been instrumental in promoting the establishment of *Leptospermum scoparium* plantations. These plantations are often established in areas of marginal land where erosion susceptibility is high, and a tension exists between deriving economic gains and improvements in stream health and water quality.

Typically, such terrain comprises several different landform units, including landslide-scarred hillslope and localised depositional units in the form of colluvial

Most incidences of shallow landsliding in the North Island of New Zealand are associated with the establishment of *Leptospermum scoparium* plantations. The research has shown that *Leptospermum scoparium* plantations can play an important role in mitigating erosion. The government-funded schemes, including the Afforestation Grant Scheme, have been instrumental in promoting the establishment of *Leptospermum scoparium* plantations. These plantations are often established in areas of marginal land where erosion susceptibility is high, and a tension exists between deriving economic gains and improvements in stream health and water quality.

Methods

Site and trial design

New Zealand, where plantings were established at the southern end of a northwest-facing scarp comprising Tertiary-aged sandstones and silty mudstones interbedded with limestone and conglomerates. The research has shown that *Leptospermum scoparium* plantations can play an important role in mitigating erosion. The government-funded schemes, including the Afforestation Grant Scheme, have been instrumental in promoting the establishment of *Leptospermum scoparium* plantations. These plantations are often established in areas of marginal land where erosion susceptibility is high, and a tension exists between deriving economic gains and improvements in stream health and water quality.

Across the study area, the overlying regolith is largely

to a range of different erosion processes, particularly

are largely undisturbed Typic Orthic Allophanic (Hewitt

Parameter	Details
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Slope group	1 ˘ ˇ šaŸ/˘ ˇ) ˇ
" ˘ ˘ «Ÿ ˘ Š--ŸŸš°Ÿa2	(µ-ŸŸ©Š°±Ÿ ŠŠ-Ÿe Typic Orthic Allophanic
Geology ³	Pliocene-age mudstone, sandstone, limestone
Erosion severity and type	Extreme shallow landsliding, slight tunnel gullyng
Vegetation type	Low producing pasture
Elevation (asl)	˘©
Aspect	Northwest facing

³ Mazengarb & Speden (2000)

Seedlings were planted in parallel lines along slope contours at a spacing of 3×3 m (i.e. 1111 stems ha^{-1}). An independent audit carried out a year after planting

Plot-based measurements

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were present within a single container supplied by the
^a_±^o_i·^o₁₄+^o_i·^a_i·^o_S·^y_o_i·^y_Y·^o_o_i·^y_Y·^o_o_i·^μ_E^o₃·^s_S·^s_S
cluster comprising numerous individual plants, each

Landform	Area (% of total)	Slope (degrees)	Regolith depth (m)	Erosion rate	Erosion type
Former landslide scars	6.6	Flat	>1	High	Shallow landslide
Colluvial slopes				Very low	Tunnel gully
Channel heads				Low	Channel widening
Channel banks			High	Channel widening	
Channel beds			High	Shallow landslide	

and based on estimated heights and general stature representative of the smallest, medium and largest trees present within PSPs on each of the landform types. All excavations were located beyond the bounds of the PSPs

Sample trees were cut at ground level and their above-ground components were then separated into branches, foliage, and stem. The separation between stems and branches for single and double leader shrubs was obvious as each stem originated at the root collar. For multi-stemmed clusters separation between stems and branches was easier. Where stems were more upright, and of larger diameter than the foliage-bearing branches. Foliage and seed pods were hand-stripped from the branches and stem.

from the ground, the root system of each plant was washed to remove adhering soil matter, photographed (Fig. 3) then partitioned into root bole (stump) and roots. Below-ground growth parameters included mean root depth and mean root spread of the lateral roots,

[illegible]

	2015	2016	2018
PSPs			6
Total PSP plants	346		
Excavated sample plants			4

[illegible]

All plant components, both above- and below-ground, weight loss was detectable then weighed to the nearest 0.1 g. Above-ground biomass (AGB) and root:shoot ratio were calculated using dry weight (g).

Data analysis

Statistical differences in incremental change in tree PSPs were assessed using unbalanced ANOVA with least-squares means (P -values) between years and/or landforms. This was also done for total AGB, total BGB, and total tree biomass of excavated plants were also assessed for differences between landforms and years using unbalanced ANOVA. All statistical analyses were considered significant at $P < 0.05$.

Allometry

From PSP measurements, power regression using the equation ($y = ax^b$), measurements of excavated foliage, branches and stem biomass, total above-ground biomass (AGB), total below-ground biomass (BGB), total root biomass (>1 mm diameter), and total root length (>1 mm diameter) were used to estimate total tree biomass. All regression equations were used to estimate total tree biomass. The regression equations were used to estimate total tree biomass. The regression equations were used to estimate total tree biomass.

Landform and age	Excavated Height (m)	PSP Height (m)	Excavated ~"fl"·◎◎	PSP ~"fl"·◎◎	Excavated RCD (mm)	PSP RCD (mm)	Excavated Can. Dia (m)	PSP Can. Dia (m)	Excavated ("š"" fl"·£
Pa ^o ·@± ² ·-									
3 years	2.0 (0.2)a	1.9 (0.1)a	7.2 (2.6)a	4.1 (0.1)a	· š · š · š · š · š · š · š · š · š	· š · š · š · š · š · š · š · š · š	· š · š · š · š · š · š · š · š · š	· š · š · š · š · š · š · š · š · š	
4 years	· >	· >	14.2 (3.4)a	6.6 (0.1)b	55.4 (13.3)a	28.1 (0.8)b	0.8 (0.1)a	1.6 (0.1)b	· š
6 years	· oe	· Ÿ	· >	· oe	· >	· oe	· >	· oe	· >
Landslides									
3 years	· š>	· š	6.6 (2.3)a	· š	35.1 (9.1)a	18.0 (0.7)d	· š · š · Ÿ	· š	· š
4 years	· š>	· >	· š	· j	· š	· š	0.5 (0.2)a	1.4 (0.1)e	· š
6 years	· š>	· Ÿ	· š	· č	· š	· j	0.5 (0.1)a	1.9 (0.1)f	· š
Colluvial slopes									
3 years	· š>	· š	· š	· š	· š	· Ÿ	· š · š · š	· š	· š
4 years	· š>	· oe	13.6 (6.3)a	· Ÿ	· š	· >	0.8 (0.2)a	1.6 (0.1)b	· š
6 years	· š>	· j	· oe	· oe	· oe	· oe	· oe	· oe	· oe
Pa ^o ·@± ² ·-									

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 after planting across all landforms, and for
 PSP-based measurements, by landform type,
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 Zealand.

	r²	P	a	b	SEE*
Excavated trees					
PSP-based measurements					
$E^a \circ_i \oplus^{\pm 2}_i$					
Landslide					
Colluvial slopes					

*Standard error of the estimate

Canopy closure and root occupancy prediction

[illegible] $\&^{-\pm\cdot\circ-}$

Changes in PSP planting density

[illegible]

missing trees across the different landforms, confounded more by large variations in the initial planting spacing both across the different landforms and among PSPs located on the same landform, than by the proportion of trees presumed to have died subsequent to planting, a

single-stemmed plants; the remainder were multi-stemmed. The proportion of single-stemmed plants was significantly higher in the 1st and 2nd years after planting, nor were these metrics significantly different between 3 and 4 years after planting, nor were these metrics significantly different between 4 and 6 years after planting, for plantings on the 1st and 2nd years after planting (Table 4).

The allocation of total AGB to stem, branches, and foliage was initially greater to branches than stems, and least to foliage. As tree height increased, most biomass was allocated to stem, and least to foliage. These trends were

The mean maximum root spread (diameter of intact root system) of $m^{1/4} \pm SS$ excavated 3 and 4 years after planting

[illegible]

[illegible]

Landform/age	Component biomass (g)			
	Foliage	Stem	Stem	Stem
3 years	3	3	3	3
4 years	3	3	3	3
6 years	3	3	3	3
Landslides				
3 years	3	3	3	3
4 years	3	3	3	3
6 years	3	3	3	3
Colluvial slopes				
3 years	3	3	3	3
4 years	3	3	3	3

[illegible][illegible][illegible][illegible]

6 years after planting, respectively, and was apportioned equally between roots and the root bole. However, for

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diameter size class

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were excavated, or distance from the root bole, roots in the
 greatest proportion of the total length of structural roots
 excavated 3 and 4 years after planting, structural roots in
 of the root bole.

[illegible]

M¹/₄±SS excavated across all landform types 3 and 4 years after planting exhibited an increase in root biomass allocation towards larger diameter roots and was relatively well-distributed between each of the distribution by diameter size class for m¹/₄±SS excavated 6 years after planting. By contrast, the root biomass of the m¹/₄±SS excavated from landslides 6 years after planting had no significant difference in root biomass allocation between each of the distribution by diameter size class.

Allometry

[illegible]

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Based on incremental changes in the crown diameter
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each of the landforms is predicted to occur at different
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even spacing of 3 × 3 m (1111 stems ha⁻¹), the crowns
«C©¼±šš»-šᵃoƳƎ «ᵃœ ±²Ų »-«¼-³ «±Ÿ°šoƳ
ōᵃ «μōκ ±®¼ j š®¼ °š° μš®šć¼ ®-šᵃoƳƎ šć¼ ®
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By comparison, for less-dense plantings established at
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closure across the wider, 4-m gap between planted rows
³ «±Ÿ Ų¼ u¼ j Ÿ¼ šu Ÿᵃᵃ ¼ μš®šć¼ ®-šᵃoƳƎ «ᵃ

Radial distance from root bole (m)

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 ° C ° S Y S ° i f C i a ° C ° C ° i R C ° » » i ° R C
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 3 and 4 years after planting n S a Y C C C i 1 4 ± S S
 excavated 6 years after planting $n=2$. Note the
 ° C i Y C R a C ° C R C ° ° ° i μ K a Y S ° ° C ° S Y S
 Y Y S a C ° ° C ° i R C ° ° » » i ° S a Y ° C S ° a « ° C i 1 4 ± S S
 were excavated from colluvial slopes 6 years after
 planting.

(continued) Table 1. Root biomass (kg m⁻²) and percentage of total above-ground biomass (AGB) for *Podocarpus totara* and *Prumnopitys ferruginea* in the *Podocarpus totara* forest. Data are presented for the three main canopy layers (canopy, overstorey, and understorey) and for the total root biomass. The data are presented for the three main canopy layers (canopy, overstorey, and understorey) and for the total root biomass. The data are presented for the three main canopy layers (canopy, overstorey, and understorey) and for the total root biomass.

Landform and Age	0–0.5 m		0.5–1.0 m		1.0–1.5 m		1.5–2.0 m		2.0–2.5 m		2.5–3.0 m	
	Root biomass	%	Root biomass	%	Root biomass	%	Root biomass	%	Root biomass	%	Root biomass	%
Laurel forest												
Year 3	3.3		3.3	4.3 (3.2)b								
Year 4	3.3	(11.1)a	3.3		3.3	1.4	3.3	0.6				
Year 6	3.3		3.3 (164.2)b				3.3 (2.2)b	1.3	3.3		3.3	
Landslides												
Year 3	3.3		3.4 (3.2)a	1.3 (1.1)b			3.3					
Year 4	(61.4)a		3.3		3.3		(61.4)a					
Year 6	(22.3)a		3.3				(22.3)a					
Colluvial Slopes												
Year 3	3.3		3.3									
Year 4	3.3	(3.6)a	3.3 (3.4)b	3.6 (3.2)a	1.1		(1.3)a					

landslides for >12 years after planting.

Based on the mean root spread (diameter) of root systems excavated from each landform, root occupancy of the soil might be expected to occur in advance of even spacing of 3×3 m (1111 stems ha^{-1}) would occur. occupancy for planting on landslide-scarred slopes had a regime where plantings are unevenly spaced (4×3 m spacing), lateral root extension across the wider 4-m gap may not occur at all on slopes that have been extensively scarred by landslides.

~ Yoe--Ya

(role in lessening the initiation of shallow slope exists between rainfall intensity/duration, landslide density, and vegetation type and maturity (Selby amount of rainfall intercepted during extreme rainfall Furthermore, while young vegetation during the initial years after establishment affords little protection storm, the reduction in storm-initiated slope failures is example, while the occurrence of landslides initiated in areas that received the most rainfall, their incidence (density) in areas of well-established, closed-canopied areas suggests that lateral root reinforcement of the soil would conditions were more conducive to root development.

Radial distance from root bole (m)

/Hf) & a. excavated 3 and 4 years after planting $n=3$, and $n=2$. Note the scale difference for roots beyond 3 years after planting.

The mechanical reinforcement of soil by roots (Watson Thus, options that promote full soil-root reinforcement trial exceeded crown widths of both the excavated trees and those measured in PSPs (Table 4), root occupancy of the soil might be expected to occur in advance of canopy closure on these landforms. Conversely, although landslide-affected slopes was also greater than their suggests that lateral root reinforcement of the soil would conditions were more conducive to root development.

[illegible]

6 years after planting ($n=22$), and (b) analysis of PSP data for planting (n = 22) in Bay, New Zealand. Note the difference in x and y scales between graphs A and B. Analysis parameters are presented in Table 1.

[REDACTED]

The study site has a climate considered near optimal for $1/4 \pm \text{SS}$ growth (McPherson & Newstrom-Lloyd 1993). The study site is a $1/4 \pm \text{SS}$ plantings chemical site factors across the different landforms with incremental change, above- and below-ground, being

[illegible]

As might be expected, root systems comprising the largest root biomass, length and diameter sizes form a higher level of soil-root reinforcement (Swanston & ... used to infer the potential lateral soil-reinforcing ability ... m of the root bole, thus the area of potential lateral soil ... double that of equivalent-aged plantings on landslides.

The development of a compact and dense root system close to the root bole was also observed during the excavation of several other indigenous and exotic species of similar age. These include the native conifers matai (*Podocarpus nelsonii*) and miro (*Podocarpus ferrugineus*) ... *Quercus robur* and redwood (*Sequoia sempervirens*) ... all species, the level of lateral soil-root reinforcement rapidly decreases as the density of roots tapers off with increasing distance from the root bole.

The mechanical interactions of woody roots with the soil medium also play an important role in tree anchorage. Therefore, one of the most important traits of a root system is rooting depth, which is species- ... New Zealand, the most common form of erosion occurs ... landslides are typically small, shallow, and translational, ... in order to anchor the soil into more stable substrate and stabilise a slope against the initiation of shallow ... (>2 mm) with the potential to provide reinforcement ...

The authors declare that they have no competing interests.

generated most of the graphs and tables, and completed the statistical analyses. All authors read and approved the manuscript.

[illegible]

Availability of data and materials

Please contact the corresponding author for data requests.

$$/_{+} \mathbf{a} \dot{\mathbf{y}} \mathbf{a} \mathbf{c}$$

This research was supported over several years from

References

YBC & Iso^a & d^a L^a | @p^a < C
 S^a S^a > μ^a C S^a ± S^a *Leptospermum scoparium* at
 Taita New Zealand. New Zealand Journal of Science,
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rainfall by hard beech (*Nothofagus truncata*) at
Taita, New Zealand. *New Zealand Journal of Science*,
16, 11-12.

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stands of *Pinus radiata*, indigenous podocarps/
hardwood forest, and improved pasture in the
New Zealand

Protective value of regenerating tea tree stands
on erosion-prone hill country, East Coast, North
Island, New Zealand *New Zealand Journal of*
Ecology 2000, 24, 1-10

in tea tree. [Abstract]. $I_{\pm} \otimes \tilde{S} \ll \mathcal{C} f l \mu \tilde{Y} \otimes \mathcal{E} \mu \rangle i^3$
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Hillslope Form and Process # 3 2 1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000 1001 1002 1003 1004 1005 1006 1007 1008 1009 1010 1011 1012 1013 1014 1015 1016 1017 1018 1019 1020 1021 1022 1023 1024 1025 1026 1027 1028 1029 1030 1031 1032 1033 1034 1035 1036 1

Evidence from near-isogenic lines that root penetration increases with root diameter and bending stiffness in rice. / *Journal of Agricultural Science* 145: 1-10

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between *Pinus radiata* (radiata pine) and *Kunzea ericoides*: Šš^a+Šš[~] " j³ : jš š^aŸ!«±®š[~]Ÿ/«®^oŸ! Science, 27(2), 216-233.

Ground and Water Bioengineering for Erosion Control and Slope Stabilization

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Site code	Easting	"
'S> i Y° i ® ±² i ·	1	"
'S> i Y° i ® ±² i ·	1	"
'S> i Y° i ® ±² i ·	1	"
Landslide scar 1	1	N6211611
Landslide scar 2	1	N6211662
Landslide scar 3	1	"
Colluvial slope 1	1	"
Colluvial slope 2	1	"
Colluvial slope 3	1	"

[illegible]

Regression	Stem area (m ²)		Canopy area (m)		Stem area (m ²)		Root area (m ²)	
	r ²	P	r ²	P	r ²	P	r ²	P
Linear						0.009		0.016
Quadratic								
Cubic								
Power								
Logarithmic						0.009		0.016