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# Inter-taxa differences in root uptake of $^{103/106}$Ru by plants

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## Abstract

Ruthenium-106 is of potential radioecological importance but soil-to-plant Transfer Factors for it are available only for few plant species. A Residual Maximum Likelihood (REML) procedure was used to construct a database of relative $^{103/106}$Ru concentrations in 114 species of flowering plants including 106 species from experiments and 12 species from the literature (with 4 species in both). An Analysis of Variance (ANOVA), coded using a recent phylogeny for flowering plants, was used to identify a significant phylogenetic effect on relative mean $^{103/106}$Ru concentrations in flowering plants. There were differences of 2465-fold in the concentration to which plant species took up $^{103/106}$Ru. Thirty-nine percent of the variance in inter-species differences could be ascribed to the taxonomic level of Order or above. Plants in the Orders Geraniales and Asterales had notably high uptake of $^{103/106}$Ru compared to other plant groups. Plants on the Commelinoid monocot clades, and especially the Poaceae, had notably low uptake of $^{103/106}$Ru. These data demonstrate that plant species are not independent units for $^{103/106}$Ru concentrations but are linked through phylogeny. It is concluded that models of soil-to-plant transfer of $^{103/106}$Ru should assume that; neither soil variables alone affect transfer nor plant species are independent units, and taking account of plant phylogeny might aid predictions of soil-to-plant transfer of $^{103/106}$Ru, especially for species for which Transfer Factors are not available.

*Keywords:* Ruthenium; Soil-to-plant transfer; Phylogeny

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## 1. Introduction

Ruthenium-106 is a fission product of radioecological importance but there have been relatively few comparisons of species differences in its uptake by plants from soil. Differences between plant species can affect soil-to-plant transfer of other radioecologically important isotopes such as $^{137}$Cs and $^{90}$Sr (Nisbet and Woodman, 2000) and might affect soil-to-plant transfer of $^{106}$Ru. Here we report a database of relative $^{103/106}$Ru uptake by 114 plant species, by collation of data we generated for 105 species with data in 5 previous studies, and analyse it using techniques established to provide a phylogenetic perspective on inter-species differences in element concentrations.

Ruthenium-103 and $^{106}$Ru are $\gamma$-emitters produced in significant quantities by nuclear fission. $^{103}$Ru has a relatively short half-life (39 d) but $^{106}$Ru has a longer half-life (368 d) and is considered a potentially significant long-term radioecological hazard in the ecosystems it contaminates. $^{106}$Ru was a significant component of nuclear-weapons testing fall-out (Walton, 1963; Ritchie et al., 1970) and it was one of the common radionuclides deposited in the Chernobyl 30 km zone (Lux et al., 1995; Krouglov et al., 1998) contributing significantly to external doses to humans (Andersson and Roed, 1994). Despite being deposited primarily in fuel particles which settled close to the Chernobyl reactor (Krouglov et al., 1998), $^{106}$Ru was detected in significant quantities in Chernobyl fall-out in, for example, Sweden (Kresten and Chyssler, 1989), Italy (Adamo et al., 2004) and Turkey (Polar and Bayülgen, 1991). $^{106}$Ru is also a contributor to effluents from Cap de la Hague (Salbu et al., 2003) and has been a focus of attention in modelling potential accidents with Pressurised Water Reactors (Renaud et al., 1999). Given the potential radioecological importance of $^{106}$Ru it is important to understand its ecosystem transfer processes, such as that from soil-to-plant.

Many studies, including some of the first radioecological studies performed, have shown that, in general, $^{106}$Ru is less available to plants from soil than $^{90}$Sr but more available than $^{137}$Cs (Nishita et al., 1956, 1961; Bunzl et al., 1984). This is reflected in soil $K_d$ values and soil-to-plant Transfer Factors (TFs) with a mean of 100 and 0.1, respectively (Sheppard, 1985). However, $K_d$ values for $^{106}$Ru in organic soils can be very large (Sheppard and Thibault, 1990) and binding to mobile organic fractions can increase its mobility (Polar and Bayülgen, 1991). Uptake of $^{106}$Ru by plants is generally greater from soils of high pH and with high base status, for example from the black soils of the Indian Subcontinent (D'Souza and Mistry, 1980). Overall, therefore, $^{106}$Ru is considered quite available to plants in many soils. Interestingly, however, much knowledge of $^{106}$Ru transfer to plants has been gained using Cl or nitrosyl forms as experimental contaminants but the deposition in the Chernobyl 30 km zone has proved relatively immobile and unavailable due to its deposition in fuel particles, probably as metallic impurities (Krouglov et al., 1998).

Species differences in $^{106}$Ru uptake by plants have been reported (Nishita et al., 1961; Handl, 1988) but compared to other radioecologically significant isotopes there is a paucity of comparisons of concentrations to which plants take up $^{106}$Ru and all such have been confined to inter-species comparisons. Recently, molecular descriptions of the evolutionary relationships (phylogeny) of many groups of organisms have been useful to analyse differences in phenotypes between taxa at many levels of the taxonomic hierarchy. New phylogenies of flowering plants have been published specifically to aid such comparisons (e.g. Soltis et al., 1999). Treating relative elemental concentration as a phenotype and mapping it to the flowering plant phylogeny have revealed significant phylogenetic effects on the relative concentration in plants of $^{137}$Cs (Broadley et al., 1999; Willey et al., 2005), Cu, Zn, Ni, Cd and Pb, (Broadley et al., 2001), Ca (Broadley et al., 2003) and Mg, K, N, and P (Broadley et al., 2004). These studies reveal that, with the exception of N and P, at least some of the inter-species differences in relative concentration can be ascribed to taxonomic levels higher than the species. This shows that, for concentrations of these elements, species have a tendency to behave as groups rather than each species behaving independently. Such phylogenetic effects not only have to be accounted for when predicting soil-to-plant transfer but might also be used as a framework for making general predictions of relative concentrations in plants. Given the paucity of TF data for $^{103/106}$Ru, a knowledge of relative concentrations for $^{103/106}$Ru might be useful to radioecologists because, for a given substrate availability, they might be used to make predictions of uptake for substrate/plant species combinations for which TFs are not available. Here, using the method established in previous studies, we report a database of relative mean $^{103/106}$Ru concentrations in plants and analyse it using a recent flowering plant phylogeny. We conclude that there is a significant phylogenetic effect on $^{103/106}$Ru uptake by plants and discuss its significance.

## 2. Materials and methods

### 2.1. Data for $^{103/106}$Ru uptake by plants

Studies in the literature were selected if they contained measurements of significant concentrations of $^{103/106}$Ru in above-ground green shoots in plants in two or more species after identical exposure in the same contaminated soil. Studies in which foliar contamination had occurred, or in which $^{103/106}$Ru activities were very low, were excluded and different experimental treatments were used as separate ‘studies’. Both $^{103}$Ru and $^{106}$Ru data were included because there is no evidence to suggest discrimination between them during uptake by plants from soil. This provided 9 ‘studies’ (‘studies’ 1–9 Table 1) from 5 sources (Bell et al., 1988; Coughtrey and Jones, 1985; Douka and Xenoulis, 1991; Handley and Babcock, 1972; Wirth et al., 1996) and included data on 12 species. One hundred and six species were chosen for experiments to complement those in the literature and provide a spread across the angiosperm phylogeny. Four species in literature data sets (*Lolium perenne*, *Lycopersicon esculentum*, *Fragaria vesca*, *Brassica oleracea*) were included in experiments. Species selection was biased in favour of herbaceous plants and crops, tree and aquatic species being more problematic to grow and expose to $^{103/106}$Ru.

Experiments with a number of radiolabelling regimes based on those previously used (Bell et al., 1988; Coughtrey and Jones, 1985; Douka and Xenoulis, 1991; Handley and Babcock, 1972; Wirth et al., 1996) showed that the procedure below, which includes $CaCl_2$ and $Na_2$EDTA to enhance Ru availability, produced high enough $^{103}$Ru concentrations to be reliably measured in plant material. Five replicate pots of each species were grown in approximately 90 g of peat-based Levington’s F2 compost (Fison’s, Ipswich, UK) for approximately 7 weeks. Plants were grown in a randomised block in a greenhouse with 16 h day and 8 h nights at c. 24 °C and 16 °C, respectively. Plants were labelled with $^{103}$Ru in the exponential phase of their growth and before they flowered, hence some taxa were slightly younger or older than 7 weeks. During radiolabelling plants were placed in randomised blocks with 350 $\mu$ Em$^{-1}$ s$^{-1}$ light for 16 h day and 8 h night. For radiolabelling 50 mL of 200 μM $CaCl_2$ and $Na_2$EDTA were added with 3700 kBq $^{103}RuCl_2$ L$^{-1}$ to give 41 kBq g$^{-1}$ substrate. The 50 mL of radiolabelled solution saturated the substrate and the excess solution was caught in saucers below the pots and in all cases was reabsorbed into the substrate during radiolabelling, so a homogenous distribution of $^{103}$Ru in the substrate was assumed. Plant shoots were harvested 96 h after $^{103}$Ru application, 1 cm above the substrate. Radiolabelling took place in 7 events in 14 blocks, each of which was treated as a separate study (‘studies’ 10–23 in Table 1). $^{103}$Ru activity concentrations were measured in dried plant samples by $\gamma$-counting in an LKB Wallac ‘Compugamma 1282’ (NaI(Tl) detector) with appropriate blanks and background corrections.

Table 1
Relative mean Ru concentrations in 114 species of angiosperm classified according to the phylogeny of Soltis et al. (1999)

| Class | Subclass | Group | Super-order | Order | Scientific name | Common name | Mean activity (±SE) (Bq/g) | Relative mean concentration | Study (*n*) |
|---|---|---|---|---|---|---|---|---|---|
| Magnoliids | Magnolidae | " | " | Magnoliales | *Annona cherimoia* | Cherimoya | 1920.1 ± 17.6 | 4.042 | 22,23 (10) |
| | | | | | *Annona squamosa* | Custard apple | 1404.7 ± 52.8 | 4.467 | 23 (5) |
| | | | | Laurales | *Chimonanthus praecox* | Wintersweet | 829.5 ± 903 | 0.149 | 11 (5) |
| | | | | Piperales | *Peperomia hederafolia* | Ivy peperomia | 312.5 ± 116.7 | 2.019 | 14 (5) |
| | | | | | *Peperomia rotundifolia* | Round-leaved peperomia | 265.1 ± 114.0 | 1.708 | 14 (5) |
| | | | | | *Houttynia cordata* | Houttynia | 997.7 ± 343.7 | 1.086 | 10 (5) |
| | Monocots | Commelinoids | " | Arecales | *Areca lutescens* | Areca palm | 128.5 ± 37.5 | −1.637 | 10 (5) |
| | | | | Commelinales | *Commelina coelestis* | Blue spiderwort | 121.2 ± 25.3 | −1.263 | 10 (5) |
| | | | | Poales | *Cyperus zumila* | Umbrella plant | 916.6 ± 293.2 | 0.956 | 10 (5) |
| | | | | | *Carex pendula* | Pendulous sedge | 165.1 ± 11.7 | 2.686 | 13 (5) |
| | | | | | *Carex comans* | Bronze sedge | 150.5 ± 85.7 | 3.225 | 13 (5) |
| | | | | | *Carex stricta* | Sedge | 98.1 ± 5.5 | −0.629 | 13 (5) |
| | | | | | *Hordeum vulgare* | Winter barley | 182.3 ± 43 | 3.515 | 4 (8) |
| | | | | | *Lolium perenne* | Rye grass | 3450,573 ± 1150,64[a] | 0.43 | 3,10 (12) |
| | | | | | *Sorghum vulgare* | Northern sugar cane | 26.2 ± 2.5 | −1.333 | 15 (5) |
| | | | | | *Triticum aestivum* | Wheat | 7.2 ± 2.9 | −1.692 | 15 (5) |
| | | | | | *Triticum durum* | Durum wheat | 4.1 ± 1.7 | −2.194 | 15 (5) |
| | | | | Zingeberales | *Canna indica* | Canna lily | 14.3 ± 4.4 | 0.294 | 19 (5) |
| | | | | | *Maranta species* | Maranta | 50.6 ± 11.8 | 3.758 | 23 (5) |
| | | | | | *Roscoea scillifolia* | Roscoea | 48.8 ± 15.2 | 3.376 | 23 (5) |
| | | | | | *Zingiber officinale* | Ginger | 93.1 ± 8.6 | 1.305 | 14 (5) |
| | | Non-Commelinoids | " | Alismatales | *Arisaema wallichianum* | Jack-in-the-pulpit | 275.8 ± 98.9 | 4.922 | 23 (5) |
| | | | | | *Arisaema tortuosum* | Jack-in-the-pulpit | 89.8 ± 43.6 | 3.927 | 23 (5) |
| | | | | | *Scindapsis aureus* | Devil's ivy | 26.1 ± 7.7 | 0.983 | 16 (5) |
| | | | | | *Philodendron hastatum* | Elephant's ear philodendron | 10.3 ± 4.0 | −0.229 | 21 (5) |
| | | | | Liliales | *Lilium formosanum* | Lily | 136.8 ± 34.7 | 4.341 | 22 (5) |

| Group | Superorder | Order | Scientific name | Common name | Mean activity (±SE) (Bq/g) | Relative mean concentration | Study (*n*) |
|---|---|---|---|---|---|---|---|
| | | | *Nemophila menziesii* | Californian bluebell | 702.2 ± 161.8 | 3.887 | 17 (5) |
| | | | *Lycopersicon esculentum* | Tomato | 33,22,102.8 ± NA, NA,24 | 3.278 | 5,6,15 (1,1,7) |
| | | | *Nicotiana glauca* | Yellow tree tobacco | 615.8 ± 239.6 | 2.557 | 12,13,15,16 (20) |
| | | | *Nicotiana sylvestris* | Tobacco ‘Only the Lonely’ | 1130.5 ± 220.8 | 1.93 | 12 (5) |
| | | | *Solanum sisymbrifolium* | Solanum | 617.9 ± 76.1 | 3.592 | 17 (5) |
| | Euasterid 2 | Apiales | *Angelica hispanica* | Angelica | 35.6 ± 14.2 | 2.578 | 21 (5) |
| | | | *Apium graveolens* | Celery | 2271.0 ± 812.7 | 2.429 | 12 (5) |
| | | | *Coriandrum sativum* | Coriander | 242.7 ± 36.0 | 2.634 | 18 (5) |
| | | | *Daucus carota* | Carrot | 99.6 ± 33.6 | 4.124 | 4 (13) |
| | | | *Hedera helix* | Ivy | 55.7 ± 8.2 | 0.572 | 14 (5) |
| | | | *Pittosporum species* | Pittosporum | 27.8 ± 6.9 | 2.821 | 22 (5) |
| | | Asterales | *Centaurea species* | Cornflower | 393.4 ± 95.4 | 3.646 | 16 (5) |
| | | | *Helianthus annuus* | Sunflower | 1366.6 ± 135.5 | 3.595 | 14 (5) |
| | | | *Lactuca sativa* | Lettuce | 47.9 ± 10.0 | 2.912 | 15 (5) |
| | | | *Tithonia rotundifolia* | Mexican sunflower | 377.2 ± 128.9 | 3.596 | 15,17 (10) |
| Rosids | Basal | Saxifragales | *Liquidambar styraciflua* | Sweet gum | 14.4 ± 3.7 | 1.045 | 13 (5) |
| | | | *Heuchera micrantha* | Alum-root | 140.4 ± 55.3 | −2.624 | 20 (5) |
| | | | *Heuchera sanguinea* | Heuchera | 36.5 ± 7.7 | 2.727 | 21 (5) |
| | | | *Bergenia purpurascens* | Bergenia | 84.5 ± 16.6 | 3.886 | 22,23 (10) |
| | | | *Bergenia cordifolia* | Bergenia | 103.1 ± 23.9 | 4.1 | 22 (5) |
| | | Geraniales | *Geranium pyrenaicum* | Pyrenian cranesbill | 594.5 ± 158.8 | 4.097 | 16 (5) |
| | | | *Geranium sylvaticum* | Wood cranesbill | 77.9 ± 9.4 | 3.573 | 21 (5) |
| | | | *Pelargonium alchemilloid* | Ladys Mantle-leaved pelargoniu | 363.2 ± 86.1 | 3.596 | 16 (5) |
| | | Myrtales | *Callistemon subdulatus* | Tonghi bottle-brush | 12.2 ± 4.8 | 0.697 | 13 (5) |
| | | | *Clarkia bottea* | Clarkia | 661.6 ± 140.3 | 3.788 | 19 (5) |
| | | | *Oenothera hookeri* | Giant Yellow evening primrose | 481.9 ± 94.8 | 1.07 | 12 (5) |

(*continued on next page*)

Table 1 (*continued*)

| Class | Subclass | Group | Super-order | Order | Scientific name | Common name | Mean activity (±SE) (Bq/g) | Relative mean concentration | Study (*n*) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Asparagales | *Allium ameloprasum* | Leek | 326.9 ± 82.6 | 0.659 | 12 (5) |
| | | | | | *Allium cepa* | Onion | 424.5 ± 396.4 | −0.588 | 12 (5) |
| | | | | | *Allium schoenoprasum* | Chives | 414.9 ± 143.3 | 0.823 | 12 (5) |
| | | | | | *Allium tuberosum* | Garlic chives | 139.7 ± 49.4 | 3.134 | 13 (5) |
| | | | | | *Asparagus officinalis* | Asparagus | 443.0 ± 148.4 | −0.753 | 11 (5) |
| | | | | | *Tigridia pavonia* | Peacock flower | 175.1 ± 29.4 | 3.068 | 20 (5) |
| | | | | | *Crocosmia masonorum* | Montbretia | 8.1 ± 4.5 | −2.114 | 21 (5) |
| Eudicots | Basal | " | " | Proteales | *Grevillea robusta* | Silk oak | 337.3 ± 258.6 | 3.25 | 21 (5) |
| | | | | | *Platanus orientalis* | Oriental plane | 145.8 ± 25.9 | 4.121 | 21 (5) |
| | | | | Ranunculales | *Papaver pilosum* | Hairy poppy | 237.6 ± 103.8 | 3.078 | 20 (5) |
| | | | | | *Papaver somniferum* | Opium poppy | 443.9 ± 229.7 | 2.875 | 18 (5) |
| | | | | | *Putsatilla vulgaris* | Pasque flower | 72.3 ± 12.4 | 3.557 | 21,22 (10) |
| | | Caryophyllids | " | Caryophyllales | *Beta vulgaris* | Beet | 100.6 ± 24.6 | 3.518 | 15 (5) |
| | | | | | *Dianthus seguiri* | Pink | 570.2 ± 112.4 | 1.277 | 12 (5) |
| | | | | | *Dianthus superbus* | Superb pink | 322.8 ± 144.6 | 3.65 | 13 (5) |
| | | | | | *Dianthus gratinopoulis* | Cheddar pink | 1994.0 ± 449.1 | 0.932 | 11 (5) |
| | | | | | *Gypsophila elegans* | Baby's tears | 1057.3 ± 287.1 | 4.113 | 19 (5) |
| | | | | | *Gypsophila paniculata* | Baby's tears | 635.6 ± 134.0 | 3.732 | 19 (5) |
| | | | | | *Silene chalcedonia* | Campion | 252.6 ± 27.0 | 2.757 | 18,19 (10) |
| | | | | | *Rheum tataricum* | Rhubarb | 1484.9 ± 170.8 | 1.612 | 10 (5) |
| | | | | | *Rumex acetosa* | Sorrel | 1533.6 ± 369.6 | 0.67 | 11 (5) |
| | | | | | *Rumex sanguineus* | Bloodwort | 330.6 ± 114.1 | 2.791 | 18 (5) |
| | Core Eudicots | Asterids | Basal | Ericales | *Vaccinium myrtillis* | Bilberry | 50 ± NA[b] | 0.354 | 8 (1) |
| | | | | | *Camellia sinensis* | Camellia (Tea) | 207.9 ± 39.9 | 1.875 | 14 (4) |
| | | | Euasterid 1 | Lamiales | *Mentha piperata* | Peppermint | 112.6 ± 34.5 | 2.972 | 20,21 (10) |
| | | | | | *Mentha spicata* | Spearmint | 958.6 ± 173.6 | 1.785 | 12 (5) |
| | | | | | *Salvia officinalis* | Sage | 3930.7 ± 1535.3 | 2.25 | 10 (5) |

| Group | Superorder | Order | Scientific name | Common name | Mean activity (±SE) (Bq/g) | Relative mean concentration | Study (*n*) |
|---|---|---|---|---|---|---|---|
| | | | *Oenothera tetragona* | Evening primrose' Sundrops' | 279.9 ± 97.4 | 0.429 | 12 (5) |
| | Eurosid 1 | Malpighiales | *Hypericum olympicum* | Dwarf St. John's Wort | 90.1 ± 13.4 | 3.165 | 13 (5) |
| | | | *Passiflora caerulescens* | Passion flower | 53.3 ± 5.6 | 3.538 | 22 (5) |
| | | Rosales | *Humulus japonicus* | Japanese hop | 81.1 ± 27.1 | 3.24 | 15 (5) |
| | | | *Elaeagnus multiflora* | Elaeagnus | 25.7 ± 1.7 | 1.701 | 13 (5) |
| | | | *Morus alba* | White mulberry | 312.7 ± 86.3 | 0.612 | 12 (5) |
| | | | *Maclura pomifera* | Osage orange | 53.8 ± 13.2 | 2.23 | 13 (5) |
| | | | *Fragaria vesca* | Strawberry | 20,80,50,2243 ± NA,529[b] | 1.585 | 7,8, 9,10,11,12 (17) |
| | | | *Rubus idaeus* | Blackberry | 20 ± NA[b] | 0.242 | 9 (1) |
| | | | *Rubus saxitilus* | Blackberry | 20,20 ± NA[b] | 0.105 | 7,8 (1,1) |
| | | | *Pilea cadierei* | Pilea | 430.9 ± 98.5 | 2.548 | 14 (5) |
| | | Fabales | *Lupinus angustifolius* | Lupin | 8212.5 ± 2778.4 | 3.162 | 10 (5) |
| | | | *Medicago lupulina* | Black Medik | 173.9 ± 79.1 | 3.269 | 13 (5) |
| | | | *Medicago sativa* | Lucerne | 533 ± 36[a] | −0.009 | 3 (1) |
| | | | *Phaseolus vulgaris* | Bean | 52,11 ± NA | 3.197 | 5,6 (1) |
| | | | *Pisum sativum* | Pea | 45.8 ± 14.5 | 0.42 | 12 (2) |
| | | | *Trifolium pratense* | Red clover | 595.5 ± 68.2 | 3.539 | 17,18 (10) |
| | | | *Trifolium repens* | White clover | 507.1 ± 119.5 | 3.713 | 19,20 (10) |
| | | | *Trifolium arvense* | Hare's foot clover | 744.0 ± 260.6 | 1.347 | 12 (5) |
| | | Curcurbitales | *Curcurbita maxima* | Pumpkin 'Blue Hubbard' | 2693.8 ± 470.6 | 4.437 | 14 (5) |
| | | | *Curcurbita pepo* | Pumpkin | 3311.5 ± 530.1 | 4.647 | 14 (5) |
| | Eurosid 2 | Brassicales | *Alyssum montanum* | Alyssum | 1720.2 ± 392.5 | 0.729 | 11 (5) |
| | | | *Alyssum saxatile* | Alyssum | 80.5 ± 16.4 | 1.682 | 19 (5) |
| | | | *Alyssum petraeum* | Alyssum | 2467.0 ± 655.3 | 2.596 | 12 (5) |
| | | | *Brassica oleracea* | Cabbage | 6.9,22.1,316.1 ± 4.1,4,49.8 | 3.139 | 1,2,4,17,20 (4,12,14) |
| | | | *Tropaeolum perigrinum* | Canary creeper | 131.7 ± 39.3 | 3.76 | 15 (5) |

(*continued on next page*)

Table 1 (*continued*)

| Class | Subclass | Group | Super-order | Order | Scientific name | Common name | Mean activity (±SE) (Bq/g) | Relative mean concentration | Study (*n*) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | *Antirrhinum X* | Snapdragon | 446.1 ± 123.7 | 3.117 | 18 (5) |
| | | | | | *Digitalis ambigua* | Large Yellow foxglove | 1853.8 ± 540.9 | 2.398 | 12 (5) |
| | | | | | *Digitalis purpurea* | Wild foxglove | 1469.0 ± 228.6 | 2.231 | 12 (5) |
| | | | | Solanales | *Ipomoea purpurea* | Purple morning glory | 694.6 ± 136.6 | 3.867 | 14,15, 16 (15) |

Studies 1–2: Bell et al., 1988, seasons 1 + 2, sandy loam soil UK, plants grown to maturity; study 3: Douka and Xenoulis, 1991; mean of harvests 2–4, clay soil pH 8 Greece with 339 Bq kg$^{-1}$ $^{106}$Ru, mean of shoots. Study 4: Coughtrey and Jones, 1985, brown sand Freckenham series, 0.29 μCi $^{103}$Ru/5 kg pot, mean of shoots. Studies 5–6 Handley and Babcock, 1972, hydroponics Hoagland's solution, 38.4 μCi/4 L, mean of three plants, new growth and old growth. Studies 7–9: Wirth et al., 1996, collected at 3 sites in Bavaria in 1992, TForg. Studies 10–23 experiments for this paper. *n* = Number of replicate measurements. Mean activities in plants from studies carried out for this paper also listed.

[a] Expressed as Bq kg$^{-1}$.

[b] Represented as TF 10$^4$.

### 2.2. Statistical analyses

Data were obtained, from the literature and experiments, for 114 species across 23 'studies'. Due to species selection, and replication between blocks, every data set had at least one species in common with another data set. Some species were represented multiple times in the data sets whilst others were present only once. Residual Maximum Likelihood (REML) analysis was used to produce a database of relative mean $^{103/106}$Ru concentrations in the 114 plant species. Studies were used as 'blocks' and species as 'treatments' in the REML analysis which was run on the statistical software package Genstat for Windows 5th Ed release 4.2 (VSN International, Oxford, UK) (Thompson and Welham, 2001) using the programme of Broadley et al. (1999, 2001, 2003, 2004). Defining blocks and treatments in this way takes account of the absolute differences in concentrations related to experimental conditions (studies) to reveal relative mean concentrations for the treatments (species). REML analyses, which here included log$_e$-transformation of raw values, can produce relative mean concentrations that are both positive and negative (Thompson and Welham, 2001). An ANOVA of REML-transformed values, coded using the ordinal phylogeny of Soltis et al. (1999) was then performed. The ordinal phylogeny of Soltis et al. (1999) was used because it was published specifically for such analyses and to enable direct comparison of Ru results with previous analyses for other elements that used this phylogeny. The categories 'Class', 'Subclass', 'Group' and 'Superorder' (Table 1) were used nominally above the level of the Order because the relationship between the Linnaean hierarchy they are derived from and higher taxonomic groups on recent phylogenies is unresolved. Normality tests used a Kolmogorov–Smirnov test in SigmaStat 3.0 for Windows.

## 3. Results and discussion

The relative mean $^{103/106}$Ru concentrations in 114 plant species, together with absolute values from each experimental study, are shown in Table 1. The REML procedure accounts for variance in absolute concentrations associated with different experimental conditions ('studies') in the input data in order to estimate relative mean concentrations for plant species across

| Group | Superorder | Order | Scientific name | Common name | Mean activity (±SE) (Bq/g) | Relative mean concentration | Study ($n$) |
|---|---|---|---|---|---|---|---|
| | | Malvales | *Cistus palhinhae* | St. Vincent Cistus | 68.8 ± 26.1 | 2.361 | 13 (5) |
| | | | *Althaea rosea* | Hollyhock | 5054.1 ± 701.7 | 1.93 | 11 (5) |
| | | | *Malva sylvestris* | Common mallow | 6570.0 ± 421.1 | 5.191 | 16 (5) |
| | | Sapindales | *Pistachia chinensis* | Chinese pistachio | 36.4 ± 6.8 | 0.712 | 18 (5) |
| | | | *Ruta graveolens* | Rue | 3041.6 ± 1667.9 | 1.046 | 11 (5) |

all studies. There were significant effects of block in the analysis confirming that values for all these species could not be compared without taking it into account. The values in Table 1 cannot, therefore, be regarded as concentration ratios or TFs for plant species under a given set of conditions but rather they are predicted relative mean concentrations across a variety of conditions, i.e. which species tend to have, relative to each other, higher or lower concentrations. There are, however, a number of factors that might interact under a particular set of conditions to produce relative concentrations somewhat different to those in Table 1. First, the length of exposure to $^{103/106}$Ru in almost all the data sets collated was acute. The relationship between concentrations produced in plants after acute and chronic exposure to $^{103/106}$Ru from the soil is little known. For other radionuclides, such as $^{90}$Sr and $^{137}$Cs, there is evidence that much uptake takes place during the exponential phase of growth (Weaver et al., 1981), as is the case with many mineral nutrients (Marschner, 1995). As majority of the species in Table 1 were

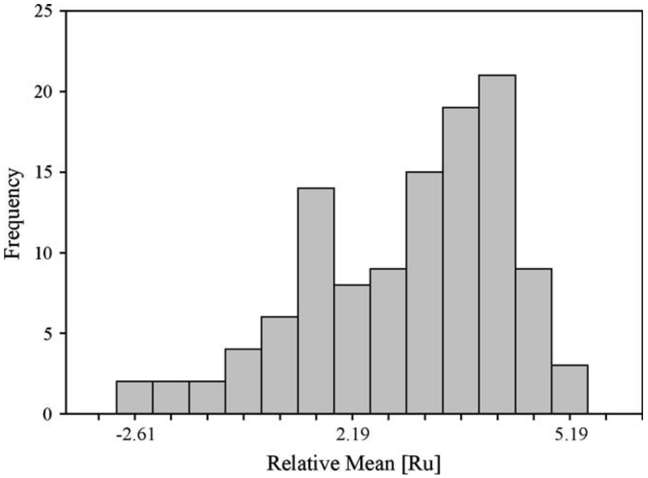


Fig. 1. The frequency distribution of relative mean Ru concentrations in 114 species of angiosperm (Kolmogorov–Smirnov distribution 0.11, $P < 0.001$).

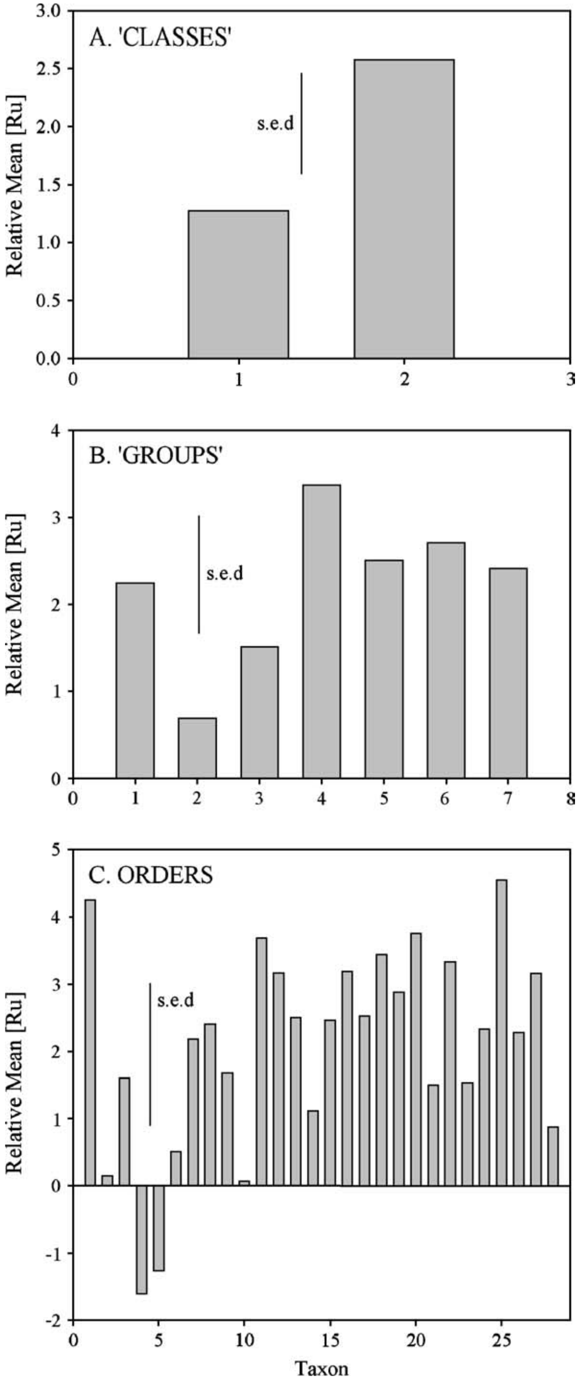
Table 2
Results of ANOVA for relative mean Ru concentrations in 114 angiosperm species classified according to Soltis et al. (1999)

| | d*f* | Sum of Squares | % Sum of Squares | Cumulative % Sum of Squares | Mean square | Variance ratio |
|---|---|---|---|---|---|---|
| Class | 2 | 3816 | 4.2 | 4.2 | 1272 | 4.46 |
| Subclass | 3 | 226 | 0.2 | 13.3 | 113 | 0.4 |
| Group | 4 | 8153 | 8.9 | 13.1 | 2038 | 7.15 |
| Superorder | 4 | 1881 | 2.1 | 15.4 | 470 | 1.65 |
| Order | 14 | 21 775 | 23.7 | 39.1 | 1555 | 5.45 |
| Family | 22 | 10 168 | 11.1 | 50.2 | 462 | 1.62 |
| Genus | 36 | 37 697 | 41.1 | 91.3 | 1047 | 3.67 |
| Residual | 28 | 7987 | 8.7 | 100.0 | 285 | |
| Total | 113 | 91 706 | | | | |

exposed during their exponential growth phase, it seems likely that the relative mean concentrations in Table 1 will relate to chronic exposures, but it is possible that this relationship is not close. Further, for $^{106}$Ru, as for other radioisotopes, the chemical species present in soil can affect its behaviour (Krouglov et al., 1998). It is possible that different compounds of $^{103/106}$Ru might not produce the same relative concentrations as those in Table 1. In fact, it is possible that a number of such edaphic factors might interact with relative $^{103/106}$Ru concentrations because all species cannot grow equally well under different conditions. There is variety in $^{103/106}$Ru compound and experimental conditions used to generate data for Table 1, which therefore provides relative mean concentrations across them, but the full range of exposure conditions might not produce results identical to those in Table 1. Overall, Table 1 does not, therefore, provide definitive relative mean concentrations between plant species. However, as the largest inter-species comparison of uptake of $^{103/106}$Ru by plants is yet to be reported, Table 1 does provide an estimate of the relative mean concentrations for a wide variety of plants and a starting point for analysing them phylogenetically.

Log$_e$-transformed relative mean $^{103/106}$Ru concentrations ranged from −2.62 to 5.19 across the 114 species in the database (Table 1), indicating that absolute concentrations might differ by more than 2000 fold ($e^{7.81} = 2465$) if all species could be grown simultaneously under the same conditions. In experimental data derived under a single set of conditions (studies 10–23) the lowest $^{103/106}$Ru concentration was 4.1 Bq g$^{-1}$ in *Triticum durum* and the highest concentration was 6570 Bq g$^{-1}$ in *Malva sylvestris*, roughly agreeing with this estimate. $^{103/106}$Ru REML values were not normally distributed but significantly skewed (Fig. 1) and there were no significant outliers that could be removed to produce normality. Overall, these results suggest

Fig. 2. Average relative mean Ru concentration in angiosperm taxa according to Soltis et al. (1999) (s.e.d. = standard error of the difference at 0.05). A: 'Classes' (for ANOVA, $P < 0.001$) 1 = Magnoliids ($n = 33$ species), 2 = Eudicots ($n = 81$). B: 'Groups' (for ANOVA, $P = 0.002$) 1 = Magnoliidae (6), 2 = Commelinoid monocots (15), 3 = non-Commelinoid monocots (12), 4 = Basal Eudicots (5), 5 = Caryophyllids (10), 6 = Asterids (24), 7 = Rosids (42). C: Orders (for ANOVA, $P = 0.004$) 1 = Magnoliales (2), 2 = Laurales (1), 3 = Piperales (3), 4 = Arecales (1), 5 = Commelinales (1), 6 = Poales (9), 7 = Zingerberales (4), 8 = Alismatales (4), 9 = Liliales (5), 10 = Asparagales (3), 11 = Proteales (2), 12 = Rannunculales (3), 13 = Caryophyllales (10), 14 = Ericales (2), 15 = Lamiales (6), 16 = Solanales (6), 17 = Apiales (6), 18 = Asterales (4), 19 = Saxifragales (5), 20 = Geraniales (3), 21 = Myrtales (4), 22 = Malphigiales (2), 23 = Rosales (8), 24 = Fabales (8), 25 = Cucurbitales (2), 26 = Sapindales (5), 27 = Malvales (3), 28 = Brassicales (2).


A. 'CLASSES'
B. 'GROUPS'
C. ORDERS
s.e.d
Relative Mean [Ru]
Taxon
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
8
-1
-2
10
15
20
25

that there is a significant range of relative mean $^{103/106}$Ru concentrations between plant species and that this range, and its frequency distribution, might usefully be considered in soil-to-plant transfer involving multiple plant species.

There were statistically significant effects of phylogeny on $^{103/106}$Ru concentrations in plants at the level of the 'Class', 'Group', Order and Genus (Table 2). Overall, 39% of the Sums of Squares was associated with the level of Order and above, and Genus was associated with the greatest % Sum of Squares. Between the plants categorized here by 'Class', the Magnoliids ($n = 33$ species) had significantly lower relative mean Ru concentrations than the Eudicots ($n = 81$) (Tables 1 and 2; Fig. 2A). Significant differences at the 'Group' level were marked by relative mean Ru concentrations that were significantly lower in Commelinoid monocots than most other groups (Tables 1 and 2; Fig. 2B). At the Ordinal level the Cucurbitales and Magnoliales had the highest relative mean concentrations but were both only represented by two species (Table 1; Fig. 2C). Of the orders with greater numbers of representatives, the Geraniales ($n = 3$) and Asterales ($n = 4$) had the highest, and the Poales ($n = 9$) the lowest relative mean Ru concentrations. The Apiales, Caryophyllales, Lamiales and Fabales had, despite some high or low values for individual species, relative mean Ru concentrations close to the overall mean (2.19). Relative mean concentrations for these higher taxa do not necessarily ensure that all species within them have low or high values but rather there are significant tendencies to low or high values. In comparison to other studies of ion concentrations in plants down to the Ordinal level, the phylogenetic signal for Ru of 39% is greater than that for P (6.8%) and N (3.3%) (Broadley et al., 2004), Cs (15%) (Willey et al., 2005), Pb (20%), Cr (23%), Cu (24%), and Cd (27%) (Broadley et al., 2001), and Na (23%) (Broadley et al., 2004), but less than that for Zn (44%), Ni (46%) (Broadley et al., 2001), K (49%) (Broadley et al., 2004) and Ca (63%) (Broadley et al., 2003).

The Commelinoid monocots have been noted to have unusually low Ca uptake (Broadley et al., 2003) and the monocots are known to have low uptake of Cs (Broadley and Willey, 1999; Willey et al., 2005), so it seems likely that the relatively low uptake of Ru reported here is part of a pattern of unusual uptake of at least some elements by plants on this clade. Certainly, given the importance of the cereals crops on this clade it is a hypothesis worth further investigation. The few relative mean Ru concentrations for the Cucurbitales and Brassicales in Table 1 suggest that these orders might have relatively high and low uptake of Ru, respectively. There are indications that for other elements these Orders also have characteristic uptake (Broadley et al., 2003, 2004) and we suggest that it might be worthwhile investigating further their uptake of Ru. The Caryophyllales have high relative uptake of Cs (Broadley and Willey, 1999; Willey et al., 2005) but the data reported here suggest that they are not unusual in their Ru uptake.

## 4. Conclusion

There are significant differences between plant species in the concentration to which they take up acute doses of $^{103/106}$Ru. Clearly, there are soil factors that affect soil availability of $^{103/106}$Ru but the data in Table 1 strongly suggest that, from a given availability, plant uptake will differ significantly between species and needs to be taken into account in understanding soil-to-plant transfer. Fig. 1 suggests that inter-species differences are not normally distributed and that parametric methods might have to be used with care for modelling differences across numerous species. A priori there is no reason why $^{103/106}$Ru concentrations should differ just between species (which is primarily a reproductive unit that can be difficult to define in plants) and the data presented here strongly suggest that radioecologists should consider taxonomic units other than the species when modelling soil-to-plant transfer of $^{103/106}$Ru. Overall, for $^{103/106}$Ru uptake species do not behave independently but are affected by phylogenetic position. This has enabled us to suggest testable hypotheses about which taxonomic units of plants have relatively high and low uptake of Ru and to make general predictions of uptake for taxa in which few TF values exist.

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