

Applications of stable and radioactive isotopes in soil science

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Development and refinement in nuclear techniques have revolutionized agricultural science. In soil science, radioisotopes have proved a blessing par excellence in terms of their potential in solving many mysteries. Many researchers have worked with radioactive isotopes (radiotracers) and have found them quite helpful in soil fertility management for quantification of biological nitrogen fixation, availability of nutrients in the soil, fertilizer use efficiency, residual effect of applied amendments, salinity of soil and water, methods of fertilizer application and relative efficiency of applied organic manures.

Total evapotranspiration and its partitioning into contributing components in many ecosystems have been successfully quantified through this technique. The suitability of plants to drought or salinity conditions was also evaluated using radiotracers utilizing the inherent concept of $\delta^{13}\text{C}$ discrimination in plants. Radioactive isotopes $^{10}\text{Be}/^9\text{Be}$, $^{14}\text{Si}/^{13}\text{Si}$, $^{87}\text{Sr}/^{86}\text{Sr}$ and ^{14}C play an important role in soil erosion, soil formation and clay mineralogical studies. ^{15}N isotopic dilution techniques are also finding favour in groundwater monitoring, soil water recharge, soil and water pollution assessments.

Keywords: Clay mineralogy, groundwater monitoring, isotope discrimination, radio tracers, salinity, soil pollution.

SIGNIFICANT advances have been made in the development and application of isotopic techniques in soil and water management. The measurement of natural variations in the abundance of stable isotopes of hydrogen, carbon, nitrogen and phosphorus in soil, water and plant components can help to identify the source of water and nutrients used by plants and to quantify water and nutrient fluxes through and beyond the plant rooting zone as influenced by different irrigation and land management practices. These developments have been possible due to the increased sensitivity of continuous flow isotope-ratio mass spectrometers (IRMS) for analysing the isotopic composition in soil-plant-water components. The natural relative abundance of carbon ($^{13}\text{C}/^{12}\text{C}$) and ^{14}C produced by atmospheric weapon testing are used for studying soil organic matter dynamics. The recent advent of accelera-

tion mass spectrometry (AMS), with its smaller samples size requirement and faster throughput capabilities, has led to a rapid expansion in the use of ^{14}C to study soil organic matter dynamics in terrestrial ecosystem¹.

Soil erosion also can be assessed by isotopic techniques based on the use of fallout radionuclides (FRN) that can integrate the last 50 years of soil distribution². ^{10}Be and ^{14}C produced cosmogenically *in situ* in soil are used for monitoring soil erosion losses and soil formation rates on very large time scale³.

On the basis of their (sources) contrasting element signatures, contamination of water sources can be evaluated and monitored with a high degree of precision⁴. Soil pollutants like ^{99}Tc that pose high risk to human welfare through the food chain are quantified and their behaviour known using inductive couple plasma mass spectrometry (ICP-MS)⁵.

This article reviews the general utility of the isotopic method involving both stable isotopes and radionuclides in soil science research.

Application of stable isotopes in soil fertility management

Sustainability of agriculture largely depends on our capacity to manage soils for better production and productivity. Use of indirect methods like fertilizer equivalence (FE) approach and measuring the apparent N recovery by difference method (Diff-Method) to determine N availability to crops, leads to highly variable results, when used for measuring the amount of N from the manures⁶. But, the use of ^{15}N as a tracer is the most powerful tool to distinguish between the fates of a particular N source and background soil N^{7,8}.

As far as quantification of biological N fixation is concerned, the isotopic method is based on the observations that two stable isotope of nitrogen (^{15}N and ^{14}N) naturally exist and the ^{15}N atoms ratio in the air is constant (0.3663%) whereas it varies in the soil from 0.360% to 0.3730% N^{15} atoms⁹. The percentage of nitrogen introduced in the system by the N-fixing plant is calculated by the isotope dilution equation¹⁰. The percentage of ^{15}N atom excess is measured with a mass spectrometer coupled with elemental analyser.

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Table 1. $\delta^{15}\text{N}$ observed in legume crops and coffee trees from the isotopic value of leaf samples

Type of legumes in association	Legume		Coffee tree leaves	
	Fixation (‰)	Legume (‰)	Association (‰) (adjacent to legume)	Ref. plant (‰) (distant from legume)
Rukoba				
<i>Flemingia macrophylla</i> *	-2.10	3.85 ± 0.6	7.55 ± 0.5	8.12 ± 0.4
<i>Leucaena diversifolia</i> *	-1.90	4.14 ± 2.0	7.63 ± 0.6	8.12 ± 0.4
Kayanza				
<i>Flemingia macrophylla</i> *	-1.20	2.86 ± 0.4	3.38 ± 0.2	3.85 ± 0.3
<i>Desmodium intortum</i> *	-1.00	1.30 ± 0.5	3.60 ± 0.3	4.50 ± 0.3
<i>Leucaena leucocephala</i> *	-1.90	-0.40 ± 0.3	1.20 ± 0.2	2.10 ± 0.2
<i>Leucaena leucocephala</i> *	-1.90	2.65 ± 0.5	2.94 ± 0.2	2.83 ± 0.3
<i>Leucaena diversifolia</i> **	-1.90	1.46 ± 0.5	4.55 ± 0.2	5.48 ± 0.3
<i>Calliandra calothyrsus</i> **	-1.42	3.82 ± 0.2	5.13 ± 0.1	4.57 ± 0.6
<i>Erythrina abyssinica</i> **	-1.15	3.17 ± 0.3	4.32 ± 0.4	3.38 ± 0.3

*Legume crop as intercrop; **Legume as shade tree.

Table 2. Effect of two legume mulches enriched in ^{15}N on the % ^{15}N a.e. (atom excess) of soil and coffee tree leaves

Treatments	% ^{15}N a.e.		% N_{dff} in coffee
	Coffee	Soil	
Control	0.0024	0.0029	
<i>Leucaena</i>	0.0171	0.0072	12.7
<i>Desmodium</i>	0.0451	0.0155	8.4

$\text{N}_{\text{dff}} = \text{N}$ derived from fertilizer.

Relative contribution of different sources to soil organic matter is obtained by labelling organic residue with ^{15}N or ^{14}C , measuring ^{14}C by liquid scintillation and ^{15}N by mass spectrometry. Determination of turnover time for different fractions on a molecular level, $^{13}\text{C}/^{12}\text{C}$ ratio which is expressed as δ value in soil system is used. $\delta^{13}\text{C}$ provides information about the stability of different soil organic fractions and the capacity of soil to act as a sink for global carbon levels on short- and long-term basis¹¹.

In Burundi (at Rukoba and Kayanza), Snoeck *et al.*¹² observed that in legume-coffee associated system, under field conditions, roughly 30% of the nitrogen effectively fixed by a legume (including biomass, roots and root exudates) was transferred to the associated coffee trees (Table 1). The quantities of N transferred by legume prunings to sole coffee trees were measured to evaluate the amount of N transferred to coffee tree via litter fall or soil and was found that around 8–12% of the N is brought through the sole litter applied as mulch (Table 2). The comparison of trials indicated that approximately 75% of N_2 is transferred through the litter fall and the remainder 25% was transferred through the soil (Table 3). The results obtained highlight that coffee tree plantations can benefit to a large extent by their association with legumes. This experiment also throws light on cultural prac-

tices needed to be adopted for the greater benefit of association.

Influence of different methods of applying radioactive phosphorus on the *E*- and *L*-values was studied by Selvaratnam *et al.*¹³, in four soil types (sandy loam (I), sandy clay loam (II), P-deficient clay loam (III) and clay loam (IV)) in Denmark, using barley, buck wheat and rye-grass for *L*-value determination. *E*-value of a soil is commonly defined as the amount of phosphorus on the surface of soil particles and in the soil solution that is exchanged with orthophosphate ions added in solution and *L*-value¹⁴, is the amount of phosphorus in the soil and in the soil solution that is exchanged with orthophosphate ions added to the soil as measured by a plant growing in the system. The four mentioned soil types (Table 4) differed greatly in their *E*- and *L*-values. The presence of carrier has no influence on the *E*-value, whereas carrier-*P* in some cases gives a lower *L*-value. Both *E*- and *L*-values depend on the method of application and the results are listed in Tables 4 and 5 respectively. This study reveals that there is no conceptual difference between the *E*- and *L*-values, only the nature of extractions and time of extraction differ. This also highlights the importance of using the same plant species and the same method of ^{32}P application when the *L*-values of different soils are compared, so that better P-fertilization is ensured thereafter.

In Senegal, through labelling experiment of an annual addition of maize and its transformation in soil during four months of millet cultivation, Feller *et al.*¹⁵ observed that the humification of half of the carbon remaining in the soil is just beginning, the utilization coefficient of straw-N and urea-N is almost similar but the losses are nil for straw-N and 50% for urea-N and in short-term experiments, the distribution pathway of C and N derived from the same addition differ and are a function of initial composition of the plant material. The results are given in Tables 6–8 respectively. This study illustrates the impor-

Table 3. Percentage of N_{dfa} in the legume crops, $X\%$ and relative % N transferred to coffee trees

Type of association	N_{dfa} (%)	X (%)	%N transferred (in % from N_{dfa})
Rukoba			
<i>Flemingia macrophylla</i> *	42 ± 5	6 ± 3	14.3 ± 2
<i>Leucaena diversifolia</i> *	39 ± 19	5 ± 4	12.8 ± 4
Kayanza			
<i>Flemingia macrophylla</i> *	20 ± 9	6 ± 4	30.0 ± 4
<i>Desmodium intortum</i> *	50 ± 5	16 ± 2	32.0 ± 3
<i>Leucaena leucocephala</i> *	52 ± 4	22 ± 1	42.3 ± 1
<i>Leucaena leucocephala</i> *	0	0	
<i>Leucaena diversifolia</i> **	48 ± 5	15 ± 4	31.3 ± 3
<i>Calliandra calothyrsus</i> **	20 ± 13	0	
<i>Erythrina obbyssinica</i> **	21 ± 4	0	

*Legume crop as intercrop; **Legume as shade tree.

Table 4. Isotopically exchangeable P (E -values) of four soils as affected by the method ^{32}P application. Means of four replicates

		E -value, g P per of Soil							
		Method of ^{32}P application							
Soil no.	Total inorganic P, µg P/g soil	Carrier-free				With carrier			
		a	b	c	d	a	b	c	d
I	250	46	40	62	87	44	44	71	66
II	110	27	11	45	54	25	23	53	54
III	270	51	29	61	72	46	39	66	92
c.v.		12	27	11	27	21	8	44	19

a, 5 g soil samples shaken with 49 ml 0.01 M $CaCl_2$ for 24 h before addition.

b, ^{32}P was added to 5 g soil samples and shaken with 5 g sand in 49 ml 0.01 $CaCl_2$ for 48 h.

c, ^{32}P was added to 5 g soil samples and shaken with 5 g sand in 49 ml 0.01 M $CaCl_2$ for 48 h.

d, ^{32}P was added to 5 g sand, air dried and shaken with 5 g soil samples in 50 ml 0.01 M $CaCl_2$ for 48 h.

Table 5. Labile phosphorus (L -value, mg P/kg soil) of four solids as affected by the method of ^{32}P application with and without carrier. Means of four replicates

Carrier-free ^{32}P		Rye grass cut 1			Rye grass cut 2			Barley			Buckwheat		
Method of application		L	M	N	L	M	N	L	M	N	L	M	N
Soil no.													
I		58	66	84	78	90	108	73	72	83	79	75	86
II		50	54	58	62	75	78	47	42	50	88	84	68
III		176	121	130	195	144	150	84	91	102	164	139	146
IV		184	139	153	199	159	172	145	131	125	218	149	167
c.v.		48	4	5	45	8	9	61	10	13	38	9	11
I		96	70	66	109	90	83	79	67	72	81	74	66
II		56	58	55	62	67	63	53	47	48	71	68	59
III		147	120	120	171	132	137	75	88	83	134	126	116
IV		153	144	136	167	150	151	116	121	120	187	142	137
c.v.		16	10	9	19	9	5	19	7	7	16	8	12

L, M and N are methods of ^{32}P application; L, The ^{32}P -solution was added to the surface of 1 kg of the soil sand mixture, covered with another kg and mixed further into 22 kg; M, The ^{32}P -solution was added to 50 g soil, air dried and mixed into a total of 24 kg of soil mixture; N, The ^{32}P -solution was added to 50 g sand, air dried and mixed into a total of 24 kg of soil mixture.

tance of using isotopic techniques combined with the size fractionation that permits to follow the fate of each amendment and contribution of each fraction in a diverse process of humification.

Trumbore¹ determined the turnover times of soil organic matter (SOM) and to partition soil respiration through ^{14}C tracer at three sites representing well-drained soils in boreal (Manitoba in Canada), temperate (central

Table 6. ^{14}C and ^{15}N distributions within the soil plant system after cultivation (plant without roots, top soil, top soil, sub-soil, losses). Results expressed as percentage of the total added labelled elements

Treatment	Plant*		Top soil		Sub-soil		Total		Losses	
	^{14}C	^{15}N	^{14}C	^{15}N	^{14}C	^{15}N	^{14}C	^{15}N	^{14}C	^{15}N
A	0	24.8	42.1	59.7	0.5	20.9	42.6	105.4	57.4	0
B		22.5		20.1		7.8		50.5		49.5

*Without roots.

Table 7. ^{14}C and ^{15}N distribution with the different fractions of top soil after cultivation. Results expressed as percentage of the top soil content after cultivation

Treatment	Soil particle size fraction									
	F2000		F200		F50		OMF		W	
A	13.1	3.9	53.4	33.3	11.9	23.3	19.2	29.8	2.4	9.7
B		3.0		6.4		7.9		21.8		60.9

*Without roots. OMF = Organic mineral fraction. W = Water soluble fraction.

Table 8. Isotope characteristics of plants and different particle size fractions of the top soil after cultivation

Treatment	Plant or soil fraction	C/N	R^{**}	E^{**}	$r = ^{14}\text{C}/^{15}\text{N}^{***}$
A	Plant*	15	0	12	0
	F2000	22	50	32	802
	F200	15	34	81	385
	F50	10	7	13	123
	OMF	9	4	5	154
	W	Nd	Nd	10	59
B	Plant*	15		45	
	F2000	Nd		34	
	F200	Nd		15	
	F50	Nd		9	
	OMF	Nd		7	
	W	Nd		67	

nd, Not determined, *Without roots; ** r -specific radioactivity expressed as percentage of SRA of initial labelled straw; $E = ^{15}\text{N}$ isotopic excess expressed as percentage of isotopic excess (E) of initial addition (straw, urea); ***Radio $r = ^{14}\text{C}/^{16}\text{N}$ is expressed in KBq per mg of ^{15}N . The ratio for the initial straw is 340.

Massachusetts in USA) and tropical forest soils (eastern Amazonia in Brazil). Comparison of their ^{14}C in soil respiration with SOM in temperate and boreal forest sites indicated a significant contribution from decomposition of organic matter fixed > 2 years but < 30 years ago. Tropical soil respiration was found dominated by C fixed < 1 year ago. Monitoring the ^{14}C signatures of CO_2 emitted from soils gave clues to the cause of seasonal and inter annual variability in soil respiration in these systems (Tables 9 and 10). These findings highlight the relative capacities of different forest soils in carbon sequestration and global C dynamics.

In Coimbatore (India), the quantification of plant available phosphorus to the residual crop of sunflower in maize–sunflower cropping sequence from organic manures, viz. farm yard manure (FYM), poultry manure (PM), bio-compost (BC) and press mud (Pr.m) was carried out through radiotracer using ^{32}P by Meena *et al.*¹⁶. PM recorded the highest value (42.68%) with respect to phosphorus derived from source. FYM as a source of phosphorus was found statistically at par with PM but superior to other treatments. The findings of the experiment are given in Table 11. The results show that emphasis has to be given to the decomposition time and mineralization of organic manures so as to reap maximum benefit from the organic applications.

Ghoneium⁶ at Ehime University in south western Japan, from his greenhouse experiment using ^{15}N -labelled biogas slurry (digested anaerobic organic residues (DAOR)) and chemical fertilizer (CF) on low fertility soil cropped with rice, observed that fertilizer-use efficiency tended to be higher for CF than DAOR. Besides, the whole plant recovery with CF treatment (70.3%) was significantly higher than that for DAOR treatment (50.5%). Relative N-use efficiency of DAOR as compared to CF was 71.8%. These findings are summarized in Table 12. This research highlights the importance of organic amendments applied, in retaining N in the soil after harvest.

Applications of isotopes in soil water movement estimations

The most frequently used environmental isotopes for hydrological investigations include isotopes of elements of

Table 9. Summary of turnover times derived from modelling radiocarbon in soil organic matter (SOM) fractions for the boreal, temperate and tropical forest soils

Site and SOM fractions	C stock (gC/m ²)	TT+ (y)	Source of mean residence time (MRT)
Boreal			
Surface moss and detritus	5800	60	¹⁴ C and C accumulation since last fire; chronosequence
Humic layer	9400	1000–1500	¹⁴ C and accumulation since deglaciation
Total to mineral (40 cm)	15,200–650–1250		
Temperate			
O leaves + roots	400	3–8	¹⁴ C of leaf and root detritus
O humics	1300	30–40	¹⁴ C and C accumulated since reforestation; CO ₂ fluxes
A/Ap low density roots	100	3–8	¹⁴ C of root detritus
A/Ap low density humics	2600	50–160	¹⁴ C of < 2 g/cm ³ fraction
A/Ap dense	600	160–400	¹⁴ C of > 2 g/cm ³ fraction
B1 low density	1200	800–1000	¹⁴ C of < 2 g/cm ³ fraction
Total to 40 cm	6200	200–310	
Tropical			
O leaves	325	< 1	Litter flux and layer inventory
A (0–40 cm) low density	830	1–3	¹⁴ C of < 2/gm ³ fraction
A dense hydrolysable	3110	10–30	¹⁴ C and C removed hydrolysis
A dense nonhydrolysable	1190	> 6000	¹⁴ C of > 2 g/cm ³ residue
Total to 40 cm	5460	1040	

Age associated with total inventories is based on the mass-weighted ¹⁴C value for all elements.

+ Turnover time of C in the plant and soil system. For homogeneous, steady-state system, this is the same as the mean age of C in the fraction, or the mean time a C atom has resided in the SOM fraction because it was fixed from the atmosphere by photosynthesis.

Table 10. Fluxes and isotopic signature of soil respired CO₂ at the three forested sites

Variable	Boreal	Temperature	Tropical
Observed flux of CO ₂ (gC-m ⁻² y ⁻¹)	200	720	2200
TT of C in SOM derived from C stock divided by 0.7 × respiration (y) +	220	12	2.5
TT determined from ¹⁴ C in SOM (y)	650–1250	200–310	1040
Δ ¹⁴ C of CO ₂ from decomposition (‰) +	+132	+165	+127
Mean age of decomposition flux (y)	30	8	3
Measured Δ ¹⁴ C of soil respiration (‰)	+110 to +120	+128	+103
Range of observed values (‰)	–97 to +160	+87 to +147	ΔNA
Mean age of soil respired C (y)	16	3	1
Fraction of total respiration derived from SOM with MRT > 1 y	40–50%	40–50%	<20%

+TT is turnover over of C in the plant and soil system.

Flux-weighted Δ¹⁴C in CO₂ derived from decomposition of soil organic matter fractions listed in Table 1. Fluxes are calculated as $k(-1/TT)$ times C inventory from Table 9. The mean age of the decomposition is calculated using the flux-weighted TT, again from Table 9. The mean value is given here for simplicity of comparison; a range of values is calculated depending on assumptions about transfer of C between SOM fractions.

ΔNA, not measured seasonally.

Table 11. Percentage of phosphorus derived from source (% p_{diff}), percentage of phosphorus derived from soil (% p_{dfs}) and A value in sunflower as influenced by sources of phosphorus

Phosphorus source	Sunflower grain yield (g pot ⁻¹)	Phosphorus (%)		
		Derived from source (% p _{diff})	Derived from soil (% p _{dfs})	A value
Control	2.77	–	–	–
FYM	4.95	22.53	77.47	12.89
Poultry manure	6.00	42.68	57.32	11.08
Bio-compost	5.05	19.66	80.34	9.55
Press mud	4.95	20.05	79.95	7.80
SSP	4.15	17.53	82.47	10.49
CD (0.05%)	1.75	6.95	6.95	

p_{diff} = Phosphorus derived from fertilizers source. p_{dfs} = Phosphorus derived from soil.

Table 12. Nitrogen use efficiency, relative efficiency and N distribution as affected by the application of chemical fertilizer (CF) and digested anaerobic organic research (DAOR)

Amendment	N use efficiency (%)	Relative efficiency (%)	N distribution (%)		
			Soil	Uptake	Loss
CF	70.3a	100	6.2a	70.3a	23.5a
DAOR	50.5b	71.8	13.2b	50.5b	50.5b

Relative uptake rate of biogas slurry N to chemical fertilizer N.

Means in a column followed by the same letter were not significantly different (Tukey–Kramer test $P = 0.05$).

the water molecule (^1H (protium), ^2H (deuterium), ^3H (tritium), ^{16}O and ^{18}O) and that of element carbon (^{12}C , ^{13}C and ^{14}C) occurring in water as constituents of dissolved inorganic and organic compounds. Application of stable isotope ratios of hydrogen and oxygen in ground water is based primarily upon isotopic variations in precipitations. Radioactive isotopes originated from cosmogenic nuclear reactions and atmospheric nuclear testing that took place up to early 1960 are useful for age determination of groundwater.

Environmental isotope techniques help in understanding the source and mechanism of recharge^{17,18}, groundwater circulation and its renewability^{19,20}, recharge areas and transit time of the aquifer²¹, hydraulic inter-relationship²², and source and mechanism of groundwater contamination²³.

Stable isotope compositions are generally reported as δ values in parts per thousand (‰). The δ values are given by:

$$\delta^2\text{H (or } \delta^{18}\text{O)} = \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \times 1000,$$

where R represents the ratio of heavier to lighter isotope in the sample and the standard respectively. $\delta^2\text{H}$ values are reported relative to international standard – Vienna Standard Mean Ocean Water (VSMOW) or Standard Light Antarctic Precipitation (SLAP). The sample is termed as depleted if the δ values are lower, and as enriched if the δ values are higher with respect to a reference.

Stable isotopic composition of water ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) is modified by processes like evaporation and condensation, and hence the recharge water in a particular environment will have a characteristic isotope signature. The signature serves as a natural tracer for water movement. Globally $\delta^2\text{H}$ and $\delta^{18}\text{O}$ of precipitation show good correlation given by Craig²⁴

$$\delta^2\text{H} = 8 * \delta^{18}\text{O} + 10.$$

This equation is called global meteoric water line (GMWL). Variation in local climatic conditions composition of precipitation, and therefore, the local meteoric

water line (LMWL) needs to be constructed for each location under study²⁵.

The application of stable isotopes to recharge problems is based on the spatial and temporal variation of the isotope of elements of the water molecules. As water evaporates from the ocean surface, the lighter isotopes (^1H and ^{16}O) preferentially move to vapour phase because of the difference in vapour pressures and diffusion velocities, and the resulting mass is depleted in lighter isotopes (^2H and ^{18}O)²⁶. When water vapour condenses, these lighter isotopes get enriched in rain compared to the remaining vapour²⁷.

The isotopic composition of precipitation is affected by season, latitude, altitude, amount and distance from the coast. The seasonal variation in temperature at a particular location generates strong seasonal variation in isotope composition of precipitation, with more depleted values occurring in the colder months than in summer²⁸. This variation acts as a tool to determine the time during the year when most recharge occurs in aquifers. Precipitation occurring at higher latitudes (polar regions) is more depleted in isotopic composition compared to tropical regions. This latitude effect is due to successive rainout from the cloud during moisture transport from the tropics to the poles. A latitude effect of -0.6‰ for $\delta^{18}\text{O}$ per degree is generally observed²⁸. The heavier isotopes in precipitation generally decrease with distance from the coast. As the air mass moves inland, the vapour gets continuously depleted in heavier isotopes due to the rainout process (continental effect)²⁹. Heavy rainfall is depleted in isotopic composition compared to light rain (amount effect). This effect results in an average depletion of -1.5‰ in $\delta^{18}\text{O}$ per 100 mm of rainfall³⁰. At higher altitudes, where temperatures are lower, precipitation will be isotopically depleted compared to lower altitudes. In the atmosphere, cooling of saturated air mass causes condensation and it releases some heat counteracting the cooling. These temperature changes with altitude is called ‘wet adiabatic lapse rate’. This rate varies with altitudes and is about 0.6°C per 100 m. The altitude effect generally varies from -0.15‰ to -0.50‰ for $\delta^{18}\text{O}$ and from -1‰ to -4‰ for $\delta^2\text{H}$ per 100 m rise in altitude²⁸. This altitude effect was used to identify the recharge areas in several hydrological investigations^{31,32}.

In Sweden, Bengtsson *et al.*³³ using natural ^{18}O isotope and artificially injected tritium (^3H) studied the percolation of soil water. In the glacio-fluvial deposits of Uppsala Esker, it was found that the groundwater recharge was distributed rather uniformly over the year, although high soil moisture flux near the ground surface was caused by single episodes (Table 13). The travel time of water particle from the ground surface to the groundwater level at about 4 m depth was two to three years. In the more heterogeneous moraine areas, the dispersion of the marked water was found considerable (Table 14). The source and nature of groundwater recharge was also known (Table 15). This experiment highlighted the importance of tracer techniques in soil water monitoring and possible contributors to groundwater recharge that can be managed on a larger scale for greater sustainability of our resource base.

In Bratislava (Most) Lichner³⁴ used radiotracer techniques (^{131}I) for *in situ* determination of the solute velo-

city, longitudinal dispersion coefficient, and bypassing ratio, as well as for estimating the impact of land-use change on area-average nitrate relative concentration profiles. It was found that the impact of land use on nitrate relative concentration profiles can be studied for small and medium cumulative infiltration only ($I = 40\text{--}54\text{ mm}$). The mean and dominant velocities obtained from breakthrough curves were significantly higher than those obtained from concentration profiles. From the results of bypassing ratio measurement, it was seen that the warm and rainless second half of April 1993 (similar situation repeated in April 2000) resulted in a preferential flow equally high in barley field as well as untilled soil with well-developed macropore system. The rain resulting in the macropore flow combined with high value of the bypassing ratio was seen as a cause in the drop of fertilization efficiency, as well as the shallow groundwater pollution in the Danubian lowland. This research highlighted that land use and cultivation practices adopted have pronounced effect on fertilizer and irrigation efficiency and the groundwater pollution. Better management of our cultivated soils will ensure sustainability in terms of increased fertilizer and irrigation efficiency, decrease in surface runoff and soil erosion and decrease in groundwater pollution by different agrochemicals.

In mountainous region of Uttarakhand (India), Shivanna *et al.*³⁵, using environmental isotope techniques, identified recharge areas of springs for rain water harvesting and groundwater augmentation for their rejuvenation and found that chemistry of high-altitude springs is similar to that of precipitation, whereas water-rock interactions contributed to increased mineralization in low altitude springs. From the stable isotopic variation in precipitation, altitude effect for the Himalayan region was found to be -0.55‰ for $\delta^{18}\text{O}$ and -3.8‰ for $\delta^2\text{H}$ per 100 m rise in altitude. Based on local geology, geomorphology, hydrochemistry and isotopic information, recharge areas were located at altitudes of 1250, 1330 and 1020 m amsl for valleys 1, 2 and 3 respectively. The recharge structures such as subsurface dykes, check bunds and contour trenches were constructed at the identified recharge areas, for controlling the subsurface flow and rain water harvesting. This research highlighted the importance of identification of possible recharge areas in the Himalayan region, so that maximum amount of water can be saved for agriculture and household facilities when springs or water sources run dry during dry season.

Table 13. Moisture flux (mm day^{-1}) at different depth and displacement rate at intermediate depths (within brackets), plot 1, Uppsala Esker, 1982)

Depth (m)	Period		
	12/3–4/5	4/5–22/7	22/7–24/9
0.35	0.92 (5.7)	0.68	–
0.65	1.13	0.68 (4.4)	0.11
1.00	1.07	0.89	0.30 (3.3)
1.20	0.90	1.00	0.45

Environmental ^{18}O as radio tracer. Glacio-fluvial deposits (sand matrix with some clay lens). Water table below 3–5 m.

Table 14. Moisture flux (mm day^{-1}) and displacement rates at intermediate depths (within brackets) at plot 2, Uppsala Esker, 1982

Depth (m)	Period	
	22/7–24/9	24/9–12/12
1.15	(6.3)	
1.55	0.72	
1.70	0.77	(1.9) (0.42)

Melt water. ^{18}O as tracer. Soil conditions same.

Table 15. Recharge (mm) estimated from oxygen-18 measurements, Uppsala Esker

	Plot-1	Plot-2	Melt/prec.
1981 melt water	120	–	130
1981 rainfall (September, November)	120	–	220
1982 melt water	180	180	190
1982 rainfall (September, November)	–	40	120
1983 melt water	–	80	130
1983 rainfall (September–October)	–	> 40	250

prec. = Precipitate.

Applications of isotopes in soil erosion and soil formation studies

There have been several attempts in the past to study soil erosion, e.g. by mass balance methods, use of U–Th series nuclides, and soil dating with different radionuclides including the cosmogenic ^{10}Be produced by cosmic rays

Table 16. Results for model soil erosion and soil formation rates for six soil profiles for ^{10}Be and ^9Be concentrations in bulk soils and in different minerals

Sample code	^{10}Be activity						
	Core length (cm)	In the top soil (atoms g^{-1})	In the soil column (atoms cm^{-2})	K_E	Erosion rate (cm y^{-1})	K_s	Soil formation rate (cm y^{-1})
Great valley (GV)	200	5.0×10^8	2.7×10^{11}	6.0×10^{-5}	1.5×10^{-3}	1.0×10^{-4}	4.1×10^{-5}
Slovenia M6	135	3.6×10^8	4.7×10^{10}	9.0×10^{-5}	2.2×10^{-3}	5.2×10^{-5}	2.5×10^{-4}
Slovenia M4	309	1.0×10^9	5.3×10^{11}	2.7×10^{-5}	6.7×10^{-4}	3.3×10^{-5}	1.3×10^{-4}
China Hat (CH)	350	5.0×10^8	5.3×10^{11}	5.4×10^{-5}	1.4×10^{-3}	1.1×10^{-4}	1.4×10^{-4}
South Mali Ferricrite (SM)	1200	1.0×10^7	2.5×10^{11}	3.0×10^{-5}	7.6×10^{-2}	3.7×10^{-2}	3.2×10^{-4}
Ivory Bauxite (IC)	1000	1.0×10^7	1.2×10^{11}	3.2×10^3	7.9×10^{-2}	2.2×10^{-2}	2.2×10^{-4}

Table 17. Inferred *in situ* ^{14}C and ^{10}Be model erosion rates and effective exposure ages of Reston (Virginia, USA) soil profile

Nuclide	Mean erosion rate (cm y^{-1})	Effective exposure age
^{14}C	$\geq 3 \times 10^{-3}$	$\leq 5.7 \times 10^3$
^{10}Be	$\leq 3 \times 10^{-4}$	$\geq 1.8 \times 10^5$

in the earth's atmosphere. The mass balance method mainly provides information on the (*in situ*) weathering rates³⁶.

Environmental traces of ^{137}Cs and $^{239-249}\text{Pu}$ produced in nuclear weapons tests and disseminated globally during the 1950s and 1960s have proven useful to quantify soil erosion on the decadal time scale³⁷. Because these transient tracers often result in characteristic depth profiles with a transition at subsurface depths, they offer some advantages over naturally produced tracers. The latter alone, however, are potentially capable of long-term averaged soil erosion rates.

The ^{137}Cs isotope ($t^{1/2} = 30.5$ years) is strongly fixed to the soil and is lost when soils are eroded. By comparing the amount of isotope in an agricultural soil with nearby areas that have not been disturbed since the 1950s, it is possible to estimate how much soil had been lost in the past 50 years. Cosmogenic radionuclides like the ^{10}Be , ^{32}Si and ^{14}C produced in the atmosphere by cosmic ray interactions and also *in situ* in soil (^{10}Be and ^{14}C) provide possible alternatives to study soil processes for a longer period of time. The atmospheric nuclides of ^{14}C and ^{10}Be are removed from the atmosphere after their production and introduced in surface soils. ^{10}Be has been studied most extensively in a variety of surface soils and soil profiles. One finds a fairly good amount of its fallout retained by the soils, in the range 10–50% of the secular equilibrium value. The real insight into ^{10}Be absorption by soils was gained with first detailed ^{10}Be studies made possible using AMS³⁸. In case of ^{32}Si , its activity has been measured in rivers, groundwaters, surface soils and oceans³⁹. The only measurement to date of ^{32}Si in soil profile is by Frohlich *et al.*⁴⁰.

The application of atmospheric ^{10}Be to soil studies is based on the fact that beryllium is particle active, i.e. it is absorbed quickly on surfaces. The depth distribution of cosmogenic ^{10}Be in soil profiles shows a great variance⁴¹. Brown⁴² observed a generally valid inverse relationship between ^{10}Be content in the soil and erosion rate.

Lal *et al.*⁴³ proposed a chronometric method for determining soil formation rates based on the cosmogenic ^{10}Be . In this model, the highest $^{10}\text{Be}/^9\text{Be}$ ratios in clays will be found at the bottom of the soil profile with ratios decreasing towards the surface, as one goes into and within the B-horizon. The results obtained by Barg *et al.*⁴⁴ validated the expectations for the $^{10}\text{Be}/^9\text{Be}$ chronometer model, and yielded soil ages in the range of 50,000 to 10 million years for the six selected soil profiles (Table 16).

In Reston (Virginia, USA), Lal *et al.*⁴⁵ studied a soil profile, which had a quartz dyke cutting into it. The estimated erosion rates based on measurement of *in situ* cosmogenic ^{14}C and ^{10}Be are shown in Table 17. The results based on the radionuclide ^{14}C are not consistent with those based on ^{10}Be . However, the data was quite consistent with a model wherein the quartz vein first eroded at the slower of the two erosion rates, and was then buried abruptly or slowly with a thickness of soil exceeding 1.3 m to result in the preferential decay of accumulated ^{14}C over ^{10}Be in the vein. The soil burial period had to be greater than two mean lives of ^{14}C , $> 2 \times 10^4$ Y to lower than $^{14}\text{C}/^{10}\text{Be}$ ratio significantly. The erosional model suggested by cosmogenic radio nuclides was found to be quite acceptable after going through the geological history of the profile. This study highlighted the role of cosmogenic nuclides produced *in situ* in soil, in soil erosion modelling for thousands of years.

In Western Australia, George⁴⁶ carried out a soil survey at 70 sites, as a part of National Reconnaissance Survey, using ^{137}Cs technique and observed that the erosion is occurring at an unsustainable rate (Tables 18a and b). About 10% of the sites had soil losses in excess of 20 tonnes per ha per year, 30% in the 15–20 tonnes per ha per year, 40% in 1–5 tonnes per ha per year and 25% sites had negligible soil loss (< 1 tonne per ha per year).

Table 18. *a*, Locations of western Australian sites sampled for ^{137}Cs . *b*, Summary of net soil loss rates in relation to land use

<i>a.</i>					
Locations	Land use	Number of sites	Annual rainfall (mm/yr)		
Kimberley	Rangelands	9	500–700		
West Pilbara–Gascoyne	Rangelands	4	< 300		
Southern rangelands	Rangelands	6	< 300		
Wheatbelt	Crop pasture	27	300–500		
Woolbelt	Pasture	7	500–700		
South west	Pasture–horticulture	17	700–1400		
<i>b.</i>					
Net soils loss (t/ha/yr)	Pasture and cropping sites	Horticulture (potato) sites	Annual pasture sites	Rangeland sites	Percentage
30–40.9	2	0	0	0	2.9
20–29.9	1	0	0	4	7.1
10–19.9	6	1	1	4	17.1
5–9.9	3	1	0	3	10
1–4.9	16	3	3	5	38.6
< 1	7	1	6	3	24.3
%	50	8.6	14.3	27.1	100

This research highlighted that mismanagement of erosion can have a serious impact on agriculture. The management of soil loss in the form of grade banks, contour system, no tillage, and stubble retention in cropping areas and careful grazing in pastured areas may provide great relief.

In a small agricultural watershed located in Austria (Mistelbach), soil erosion studies by Mabit and Klik² used a combined approach based on conventional runoff plots measurement and FRN approaches (^{137}Cs and ^{210}Pb). The study design consisted of three runoff plots (3 m \times 15 cm) including a conventional tilled plot, a conservation tillage plot and one plot under direct seedlings and soil erosion rates of 29.4, 4.2 and 2.7 t ha⁻¹ yr⁻¹ was obtained from the data collected over a period (1994–2006) for the conventional tilled plot, conservation tillage plot and direct seeding treatment respectively. In order to test the use of FRN tools a potential reference site (undisturbed forest with in Mistelbach watershed) was chosen and a classical exponential depth distribution of ^{137}Cs activity was found with 90% of the ^{137}Cs in the first 15 cm and no ^{137}Cs below 20 m. The initial fallout was evaluated at $1954 \pm 91 \text{ Bqm}^{-2}$ ($n = 76$) with a coefficient of variation of 20.4%.

Two 1 m soil profiles were collected in the sedimentation area and analysed using the ^{137}Cs method. The areal activities of ^{137}Cs were converted into soil movement (t ha⁻¹ yr⁻¹) using the mass balance model (MBM 2) and linked with the net erosion rates provided by the 13 years plot erosion measurements. A sedimentation rate of 13.2–65 t ha⁻¹ yr⁻¹, corresponding to an average layer deposition of 0.9 and 4.7 mm yr⁻¹ during 1954–2007 was evaluated from the ^{137}Cs data. This contribution demonstrates the complementarities of erosion plots and radio isotopic

method to assess erosion and sedimentation processes under different conservation cropping practices.

Application of stable isotopes in water management

Hydrogen and oxygen as constituents of water can exist as light and heavy isotopes. These isotopes can be used to identify water losses through evaporation from soil surface because the light isotopes (^1H and ^{16}O) evaporate more readily than the heavy isotopes (^2H and ^{18}O). The natural isotopic ratios of hydrogen (H^2/H^1) and oxygen ($^{18}\text{O}/^{16}\text{O}$), which are often expressed as delta units ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) in soil water, water vapour within a plant canopy and plant leaves can provide estimates of soil evaporation and plant transpiration⁴⁷. Such information will enable irrigation and land management practices to be developed to minimize soil evaporation and channel this water for crop production.

Change in the isotopic composition of hydrogen ($\delta^2\text{H}$) over a 10-day sampling period following surface irrigation of olive trees in Morocco indicated that soil evaporation as a proportion of total water removal (evapotranspiration) from both soil and crops ranged from 0% prior to irrigation to 31% after surface irrigation⁴⁷. These results highlighted that soil evaporation under the environmental conditions studied was substantial, indicating that any management factors that minimize soil evaporation such as drip irrigation can be expected to significantly improve water-use efficiency (WUE). The results are given in Tables 19 and 20 respectively.

Partition of transpiration overstorey trees from that of understorey grasses in the south west of USA in the

Table 19. Summary of linear regression analysis from keeling plots of atmospheric water vapour

Sampling period	<i>N</i>	Slope	y-Intercept	<i>R</i> ²	Significance of <i>F</i> statistic
DOY 303					
10:00–12:00 h + 14:30–16:30 h	27	–630 (118)	–40 (13)	0.53	<i>P</i> < 0.001
DOY 308					
10:30–12:30 h	12	–771 (115)	–57 (8)	0.82	<i>P</i> < 0.001
14:30–16:30 h	15	–723 (42)	–63 (3)	0.95	<i>P</i> < 0.001
DOY 310					
10:30–12:30 h	14	–594 (57)	–57 (4)	0.90	<i>P</i> < 0.001
14:30–16:30 h	15	–869 (198)	–48 (16)	0.56	<i>P</i> < 0.001
DOY 313					
10:30–12:30 h	15	–295 (35)	–57 (7)	0.85	<i>P</i> < 0.001
14:30–16:30 h	13	–300 (24)	–52 (5)	0.93	<i>P</i> < 0.001

Values in parenthesis represent 1 S.E. of the parameter estimate.

Table 20. Estimates of ph $\delta^2\text{H}$ value of evapotranspiration (δ_{ET}) from Table 19 and the isotope values of plant transpiration (δ_{T}) and soil evaporation (δ_{E}) sources for each sampling period

Sampling period	δ_{T}	δ_{E}	δ_{ET}	<i>F</i> _T	<i>F</i> _E
DOY 303					
10:00–12:00 h + 14:30–16:30 h	–44 (2)	–131 (2)	–40 (13)	1.05 (0.15)	–0.05 (0.15)
DOY 308					
10:30–12:30 h	146 (1)	–123 (5)	–57 (8)	0.86 (0.10)	0.14 (0.10)
14:30–16:30 h		–120 (5)	–63 (3)	0.77 (0.04)	0.23 (0.04)
DOY 310					
10:30–12:30 h	–46 (1)	–106 (4)	–57 (4)	–0.82 (0.07)	0.18 (0.07)
14:30–16:30 h		–120 (4)	–48 (16)	0.97 (0.22)	0.03 (0.22)
DOY 313					
10:30–12:30 h	–41 (1)	–93 (2)	–57 (7)	0.69 (0.13)	0.31 (0.13)
14:30–16:30 h		–86 (2)	–52 (5)	0.75 (.11)	0.25 (0.11)

Also shown are the estimated fractions of evapotranspiration from tree transpiration (*F*_T) and soil evaporation (*F*_E). Values in parenthesis are 1 S.E. of the means. Data from midday and afternoon sampling on DOY 303 were combined.

post rainy period by measuring natural variations of both $\delta^2\text{H}$ and $\delta^{18}\text{O}$ indicated that the total water removal (evapotranspiration) from the ecosystem was 3–4 mm/day of which 70% was from tree transpiration, 15% from the transpiration of grass layer, and 15% from soil evaporation⁴⁸. The study highlighted that overstorey trees can minimize soil evaporation, thus improve the overall WUE of the studied ecosystem.

The International Atomic Energy Agency (IAEA) sponsored research in a coordinated research project on 'Use of nuclear techniques for developing integrated nutrient and water management practices for agro-forestry systems' has demonstrated that natural variation in the abundance of ^2H and ^{18}O in the soil, plant and water can be used to quantify the contribution of hydraulically lifted water from the subsoil (4–5 m) by deep rooting trees growing in association with grasses or crops in the dry Savannah regions of Africa (e.g. in Burkina Faso and Niger)⁴⁹. Hydraulic lift is a process of water movement from subsoil to the top soil through plant roots. This

process could be one of the features contributing to the success of tree crop association growing in Parklands in the dry savanna of the West African Sahel.

The currently developed Food and Agriculture Organization (FAO) crop water productivity model 'Aqua crop'⁵⁰, which aims at predicting yield response to water for major field and vegetable crops under a range of irrigation and land management practices requires a range of data on transpiration and evaporation. These two components of evapotranspiration can be separated by using stable isotope techniques. This management tool will be useful to manage water in both rainfed and irrigated farming systems around the world.

Use of carbon stable isotopes to select and evaluate drought-tolerant plant species

Carbon, the major building block of carbohydrates and proteins in plant tissues, contains both light and heavy

carbon stable isotopes (^{12}C and ^{13}C). The measurement of natural variations in the abundance of ^{13}C and ^{12}C in plant materials is increasingly being used to select and evaluate plant cultivars that can withstand drought. During drought, less carbon, particularly ^{13}C from the atmosphere, is taken up by plants for growth because of plant stress, thus creating a major variation in the natural isotopic ratios of ^{13}C and ^{12}C in plant materials. A plant cultivar which is resistant to water scarcity should display less depletion in ^{13}C compared to a susceptible cultivar. Such discrimination against ^{13}C ($\delta^{13}\text{C}$) in plant tissues has been successfully used in the selection of drought-resistant barley, wheat, rice and peanut⁵¹⁻⁵³. Besides acting as a surrogate for WUE, carbon isotope discrimination (CID) measured in different plant parts at harvest can be used as an historical account on how water availability varied during the cropping season⁵⁴. Transpiration efficiency of chickpea grown under stress conditions was estimated by Kashiwagi *et al.*⁵⁵ through $\delta^{13}\text{C}$ discrimination technique measurements and the findings of their study are listed as Table 21.

IAEA through a Coordinated Research Project (CRP) 'Nutrient and water management practices for increasing crop production in rainfed arid/semi-arid areas' has shown that the CID technique was successfully used as a diagnostic tool for predicting WUE and wheat grain yield⁵⁶.

Application of isotopes in soil and water pollution evaluations

Nuclear energy generates many radioactive wastes containing fission products and management of these wastes is inseparable from the peaceful use of nuclear energy. ^{99}Tc is one of the most important long-lived fission products because the nuclide has a long-life (2.1×10^5 y) and it is fairly abundant as it is produced by fission of ^{235}U and ^{239}Pu at about 6% yield. Additionally, its high mobility in geological barrier means that ^{99}Tc dose assessment for humans is especially important. Similarly, steady

increase in the salinity of most of the major aquifers being used for water supply in the arid and semi-arid regions of Africa, Asia and west Asia provides evidence of water quality deterioration. This salinization is often due to inflow of saline dense water during heavy withdrawals of fresh water from coastal aquifers and/or mobilization of saline formation waters by over-exploitation of inland aquifer systems. Water pollution (salinization) cases due to extensive irrigation and use of fertilizers and other pesticides are also growing. Because there are several sources for the groundwater quality deterioration, it is necessary to characterize the specific processes involved. Isotope techniques are particularly effective for identifying the source of salinity and renewability of groundwater. Fundamental relationship between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ and between $\delta^{18}\text{O}$ and salinity is shown in Figures 1 and 2 respectively.

Radiotracer experiments were carried out to investigate the behaviour of ^{99}Tc in paddy field in Japan⁵. The

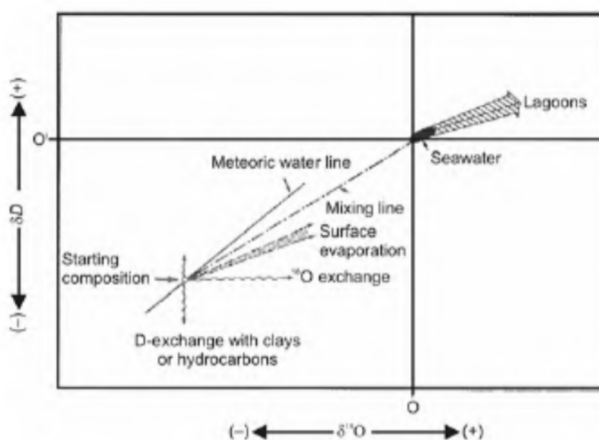


Figure 1. Change in isotopic composition of water, associated with different salinization processes: δD versus $\delta^{18}\text{O}$ (IAEA technical report series 210, 1981).

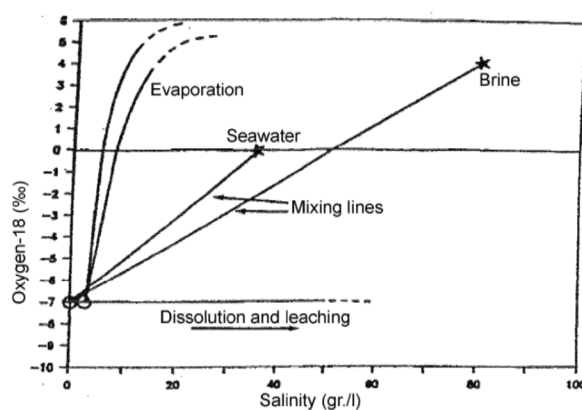


Figure 2. Change in isotopic composition of water, associated with different salinization processes, $\delta^{18}\text{O}$ versus salinity (Gonfiantini and Araguas, Symp. Tecnología de la Intrusión en acuíferos costeros, Ponencias Internacionales, 1, IGME Madrid, 1988).

Table 21. Analysis of variance and its significance for water schemes, genotypes, and their interaction for carbon isotope discrimination ($\delta^{13}\text{C}$), and transpiration efficiency (TE) in 10 chickpea genotypes grown under well-watered (control) and drought-stress conditions in a pot experiment

Source of variation	Mean sum of squares and significance level*	
	$\delta^{13}\text{C}$	TE
Irrigation scheme	146.83**	20.78**
Genotype	1.25**	0.49**
Genotype \times irrigation scheme	1.56**	0.05 NS
Residual	0.16	0.03

*Significant at ** = <0.001 level; NS = Not significant.

Table 22. Concentrations of ^{137}Cs and ^{99}Tc in soils collected in Japan on a dry weight basis and activity ratio of ^{99}Tc to ^{137}Cs

Soil type	<i>N</i>	^{137}Cs (Bq/kg) decay corrected to 2001.1.1	^{99}Tc (mBq/kg)	Activity ratio $^{99}\text{Tc}/^{137}\text{Cs} (\times 10^{-3})$
Paddy fields	9	1.7–14.0	6.1–88	1.1–70
Upland fields	6	< 1.1–7.7	4.3–7.7	0.7–3.8
Other soils	6	< 1.1–144	7.0–29	0.2–1.0
				0.33 (theoretical ratio)

Table 23. $\delta^{15}\text{N}$ results across all sampling events of Butler Spring from November 1999 through October 2004

$\delta^{15}\text{N}$ values (‰)	Potential $\text{NO}_3\text{-N}$ source	November 1999 through October 2004
		# samples (% samples)
–5 to +5	Commercial fertilizer	29 (64.4%)
+5 to +10	Organic nitrogen in soil or mixed source	16 (35.6%)
>10	Animal or human waste	0 (0.0%)
Total		45 (100%)

concentration of global fallout ^{99}Tc collected from paddy fields was 6–88 m Bq/kg dry and activity ratios of ^{99}Tc to ^{137}Cs ranged from 1.1×10^{-3} to 7.0×10^{-3} with an average of $(4.8 \pm 2.1) \times 10^{-3}$ (Table 22). These results imply that there was a tendency for ^{99}Tc to accumulate in rice paddy fields.

Two technical documents published recently by IAEA on isotope field applications for groundwater studies in the Sahel and in the Middle East respectively in 1993 and 1996 provided indepth analysis of isotope results in the aquifer studied as well as a basis for more effective planning for further isotopic investigations in these two regions^{57,58} and this work emphasized that there is further need of research in this field, particularly in reference to multiple isotope applications for more precise information.

Following ISDA (Idaho State Department of Agriculture) testing procedures, $\delta^{15}\text{N}$ testing of Butler Spring (Gooding County, Idaho) suggested a fertilizer source of $\text{NO}_3\text{-N}$ contamination⁴, taking the typical $\delta^{15}\text{N}$ ranges for different sources of $\text{NO}_3\text{-N}$ given by Kendall and McDonnell⁵⁹ as reference standards. The findings of this experiment are listed in Table 23. Besides proposing continued monitoring of the project area and isotope testing, ISDA recommended that growers and agrichemical professionals conduct nutrient and irrigation water management evaluation. Besides, producers should follow the Idaho Agricultural Pollution Abatement and Natural Resources Conservation Service's Nutrient Management Standard.

Conclusions

Isotopes play a significant role in providing solutions in soil water, plant nutrient management to improve food

security and environmental sustainability. Isotopes can be used in studies to:

- Improve FUE and sustainability of soil fertility, soil quality and water quantity and quality for adjustment or downstream communities.
- Develop water and nutrient efficient crops varieties.
- Assess farm water and irrigation management techniques that increase WUE by crops.
- Assess soil erosion rates.
- Assess soil profile and soil formation rates.
- Assess the recharge capacity of springs.
- Assess relative transport of solutes in the soil profile.
- Promote integrated natural resource management within agricultural catchment.

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