SOIL-PLANT-ATMOSPHERE MODELING IN THE CONTEXT OF RELEASES OF ^{14}C AS A CONSEQUENCE OF NUCLEAR ACTIVITIES

Laura Limer[1,2] • Ryk Klos[3] • Russell Walke[4] • George Shaw[5] • Maria Nordén[6] • Shulan Xu[6]

ABSTRACT. The need to address radiological impacts from radiocarbon released to the biosphere has been recognized for some time. In 2011, the Swedish Radiation Safety Authority (SSM) commissioned a study to develop a ^{14}C model of the soil-plant-atmosphere system that would provide them with an independently developed assessment capability. This paper summarizes that study, which comprised a review of contemporary models, the development of a new conceptual model, SSPAM^{14}C, and the application of SSPAM^{14}C to a set of experimental data relating to the atmospheric exposure of cabbages.

INTRODUCTION

The need to address radiological impacts from radiocarbon released to the biosphere has been recognized for some time. However, because of its role in biological processes and its ecological cycling, the standard methods employed to model long-term radionuclide transport and accumulation in the biosphere cannot be used satisfactorily for ^{14}C. The degree of complexity in any ^{14}C model used must be balanced against the availability of supporting data and the assessment context.

Following Swedish Nuclear Fuel & Waste Management Co.'s (SKB) safety assessment of the low- and intermediate-level waste facility at Forsmark (SFR), the importance of ^{14}C in long-term dose assessments in Sweden has been re-emphasized (Thomson et al. 2008). The potential impacts associated with ^{14}C in the biosphere have also been evaluated as being significant in other organization- and country-specific assessments (e.g. Hjerpe et al. 2010), to the extent that the international BIOPROTA forum has carried out a series of studies of ^{14}C modeling (Limer et al. 2012). Outcomes from these studies indicate that the choice between dynamic and equilibrium assessment models is of particular interest, raising the issue as to whether dynamic models are useful and/or necessary. Further, the complex processes governing carbon exchanges within the soil and between the soil and the atmosphere are not always well understood, and thus are difficult to represent appropriately in assessment models. Another difficulty surrounding the conceptual model for ^{14}C concerns the identification of conditions under which mixing and isotopic equilibrium may reasonably be assumed, particularly within the atmosphere.

In this study, a review of existing contemporary ^{14}C models has been performed, considering models developed to assess operational and accidental releases of ^{14}C from surface facilities and also those developed for safety assessments associated with the disposal of ^{14}C-containing radioactive materials. Following on from this review, a model, SSPAM^{14}C, has been developed and is described herein. SSPAM^{14}C has been applied to a data set from a study carried out at Imperial College London that involved a series of experiments in which the ^{14}C activity concentrations in a variety of plants were measured following an atmospheric release of ^{14}C-labeled carbon dioxide (Tucker and

[1]Limer Scientific Consulting Limited, 2 Cairn Brae, Newton-le-Willows WA12 9FW, United Kingdom. Also: Limer Scientific Consulting, House 7, 316 Jianguo Xi Lu, Shanghai 200031, China.
[2]Corresponding author. Email: laura@limersc.com.
[3]Aleksandria Sciences Limited, 37 Coverdale Road, Sheffield S7 2DD, United Kingdom.
[4]Quintessa Limited, The Hub, 14 Station Road, Henley-on-Thames, Oxfordshire RG9 1AY, United Kingdom.
[5]School of Biosciences, Room C29 Gateway Building, Sutton Bonington Campus, University of Nottingham, Sutton Bonington, Leicestershire LE12 5RD, United Kingdom.
[6]Swedish Radiation Safety Authority (SSM), Solna strandväg 96, SE-171 16 Stockholm, Sweden.

Proceedings of the 21st International Radiocarbon Conference edited by A J T Jull & C Hatté
RADIOCARBON, Vol 55, Nr 2–3, 2013, p 804–813

Shaw 1997). Some of these data have previously been used in the IAEA's EMRAS program (IAEA 2008). The results of our model review and development study are discussed with a view both to the need for further research and implications for model development.

REVIEW OF EXISTING CONTEMPORARY MODELS

Given the recognized importance of ^{14}C with respect to its potential impacts within the biosphere, there are already a considerable number of organizations that have developed models to assess these potential impacts associated with a range of nuclear-related activities. The models used by the various organizations fall into 2 broad categories. One subset of the models considered have been developed to consider the potential implications of ^{14}C releases either through the routine operation of nuclear facilities, or following some form of incident (human or natural). The other subset of models have been developed to consider the implications of ^{14}C releases following the disposal of ^{14}C-contaminated wastes, either in near-surface or geological disposal facilities.

Operational and Accidental Release Models

Small amounts of ^{14}C are generated during the operations of all kinds of nuclear power plants due to capture of neutrons by nitrogen, carbon, or oxygen, present as components of the fuel, moderator, structural hardware, or impurities (NCRP 1985). A fraction of the generated ^{14}C is released during normal operation of nuclear power plants, mainly in 2 chemical forms: oxidized, i.e. carbon dioxide (CO_2); and reduced, which mostly is in the form of CH_4 (Walker and Otlet 1999). As well as nuclear power plants, ^{14}C is licensed for use in radiopharmaceuticals and research, and may also enter the surface ecosystem as a result of an accidental release.

Releases from nuclear power plants, routine or accidental, and from other facilities considered in this category, are not continuous because they relate to specific operations or incidents. Consequently, some released radionuclides do not reach equilibrium in the environment. For this reason, some models for routine and accidental atmospheric releases consider processes that might vary over a growing season and, in some instances, a degree of diurnal variation may exist as well.

Waste Disposal Models

The need to address radiological impacts from disposal of radioactive waste containing ^{14}C has been recognized for some time (e.g. Bush et al. 1984). Particular interest remains in improving the assessment of possible annual individual doses to members of hypothetical exposure groups arising from releases of ^{14}C to the biosphere from deep and shallow radioactive waste disposal facilities, e.g. the Swedish SFR facility (Thomson et al. 2008), the UK's surface low-level radioactive waste disposal facility (Limer et al. 2011a,b) and site-generic models for a variety of waste types, including ion exchange resins/process water (Magnusson et al. 2008) and graphite (Limer et al. 2010).

Model Comparison

The models considered in this review are summarized in Table 1, with the key observations from the review summarized in Table 2. Irrespective of the source term, a specific activity approach is used to determine the plant ^{14}C concentration. In a specific activity approach, it is assumed that the ^{14}C reaches equilibrium in some components of the system in the same proportions with stable carbon. The movement of ^{14}C and stable carbon is then treated dynamically between some model compartments, and not others.

$$^{14}C_{plant} = {}^{14}C_{plant\,environment} \cdot \left(\frac{^{stable}C_{plant}}{^{stable}C_{plant\,environment}} \right) \tag{1}$$

Typically the soil, if explicitly represented, and atmospheric compartments are modeled dynamically. In the majority of models developed for application to short-term releases, the plant is also given a degree of dynamism by considering isotopic dilution due to plant growth (e.g. Sheppard et al. 2006a; Keum et al. 2008).

Table 1 Models considered in the qualitative review.

Model type	Agency/Organization	Model name(s)	References
Operational and accidental release	UK Food Standards Agency	STAR, PRISM, sewage sludge	Smith et al. 1994; Maul et al. 2005; Thorne et al. 2003
	Studsvik	POM^{14}C	Aquilonius and Hallberg 2005
	Canadian Standards Agency	N288.1	CSA 2008
	Électricité de France	OURSON	Sheppard et al. 2006a,b
	Korea Atomic Energy Research Institute	*Unnamed*	Keum et al. 2008
	Japanese collaboration	*Unnamed*	Tani et al. 2011
	Institut de Radioprotection et de Sûreté Nucléaire (IRSN)	TOCATTA	Aulagnier et al. 2012; Le Dizès et al. 2012
Waste disposal	UK Nuclear Decommissioning Authority Radioactive Waste Management Directorate	Enhanced RIMERS	Thorne 2005; Thorne and MacKenzie 2005
	SKB and Posiva	*Unnamed*	Avila and Pröhl 2008
	Agence nationale pour la gestion des déchets radioactifs	AquaC_14	Albrecht 2010; Albrecht and Miquel 2010
	Low Level Waste Repository Ltd	Thorne-Limer	Limer et al. 2011a,b

Table 2 Key observations from qualitative model review.

Aspect of model	Operational models	Waste disposal models
Time steps	Often subannual	Equilibrium conditions or annual average assumed
Source	Gas from above ground Irrigation water Short-term, episodic	Gas from below ground Upwelling water Irrigation water Long-term
Soil	Not always explicitly modeled. One or multiple compartments.	
Plant	Often multiple compartments Dynamic plant growth Isotopic dilution due to new growth	Typically a single compartment Static plant biomass No isotopic dilution
Atmosphere	Sometimes multiple compartments	
Plant ^{14}C concentration	Specific activity approach (photosynthesis)	Specific activity approach (photosynthesis) Sometimes root uptake

In instances where the source term is ^{14}C-labeled gas, consideration needs to be given as to whether the gas is CO_2 or CH_4. Whereas CO_2 is readily available for plant uptake (via photosynthesis), CH_4 needs to be oxidized to CO_2 before it is available to the plants (e.g. Le Mer and Roger 2001). The degree of oxidation will depend upon the soil microbial population present. Any $^{14}CH_4$ that is oxidized, either in the atmosphere, soil, or water, is available for subsequent uptake and assimilation by plants as $^{14}CO_2$. ^{14}C in plants can then be ingested and transferred to animals and humans. Where multiple plant compartments are used, then consideration must be given to which compartments are ingested by animals and humans, as these compartments may differ in both stable and ^{14}C concentrations.

Although there is some limited evidence to suggest that up to a few percent of a plants carbon might result from direct uptake by roots (Vourinen et al. 1989; Sheppard et al. 1991), it is generally considered that photosynthesis is the dominant, if not only, means by which plants obtain carbon. Given this, it is necessary to consider the profile of photosynthesis through the plant canopy as well as that of the profile of $^{14}CO_2$. There is an argument that the profile of the uptake of carbon is dependent upon the canopy density and the penetration of light through the canopy (Figure 1; Monsi and Saeki 2005). Further, as indicated in Figure 1, it is possible that the greater plant mass of photosynthetic issue is found in the upper part of the plant canopy, particularly for a broadleaf plant (Figure 1a).

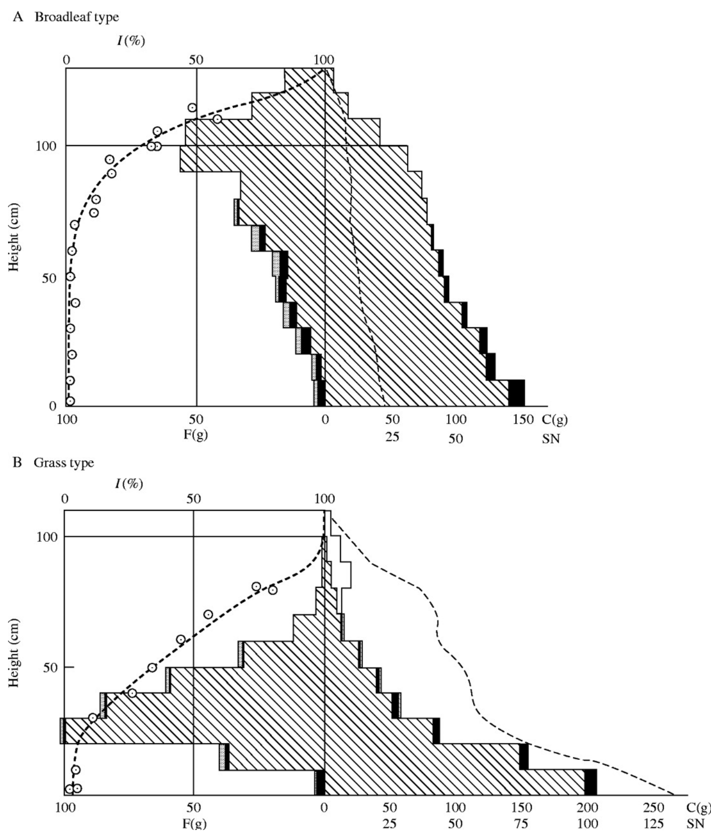

Figure 1 Productive structure of some plant communities. The dashed thick line shows the relative light intensity (*I*, %). (A) Broadleaf type: *Chenopodium album var. centrorubrum*-consociation, measured on 28 June 1949. (B) Grass type: *Pennisetum japonicum*-consociation (with fruits), measured on 28 September 1949. F = Fresh weight of the photosynthetic tissue in g per 50 × 50 cm^2. C = fresh weight of the non-photosynthetic tissue in g per the same area. SN = stem number in 50 × 50 cm^2. Reproduced from Monsi and Saeki (2005).

For a release of ^{14}C from an aboveground source, it might be argued that the profile of ^{14}C in the plant canopy atmosphere would decrease towards the bottom of the plant. Particularly in the instance of a broadleaf plant, this may be a similar pattern as the plant biomass. However, the profile of ^{14}C in the plant canopy following a release from below ground may not follow the same pattern as the plant biomass. In this instance, it would be reasonable to argue that the ^{14}C concentration in the canopy air would decrease towards the top of the plant canopy, i.e. potentially behave in an inverse manner to the plant biomass. The implications of assumptions with respect to the plant biomass distribution and the $^{14}CO_2$ distribution in the plant canopy profile in a model that considers the plant and atmosphere each as multiple compartments are discussed further in Limer et al. (2013).

SSPAM^{14}C: CONCEPTUAL AND MATHEMATICAL MODEL

In order to enable in-depth review of license applications submitted by operators, SSM needs to have independent modeling capacities for assessing the safety associated with releases of radionuclides to the surface environment following the disposal of radioactive waste, operational releases of radionuclides, and incidents or accidents leading to acute releases of radionuclides. If SSM were to use a single model for the assessment of all these release scenarios, then the model must be able to accept a variety of source terms (i.e. gaseous and liquid discharges from above and below ground), and also to consider processes within the ecosystem on a range of timescales. Bearing this in mind, an 11-compartment model (shown in Figure 2) has been developed for SSM. The model, as presently configured, considers each aspect of the soil-plant-atmosphere system by using the maximum number of compartments for each aspect as have been used in pre-existing models. Experimental data may then be used to justify model simplifications in the future.

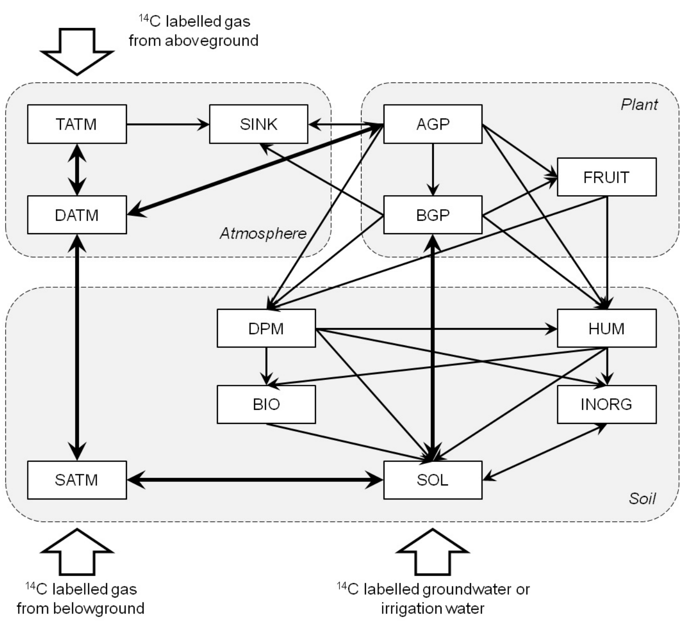

Figure 2 SSPAM^{14}C model structure. Two-way exchanges are indicated by thicker arrows.

The model has 6 soil compartments (DPM – decomposable plant material; HUM – humic substances; BIO – biota; INORG – inorganic material; SOL – dissolved C; and SATM – soil atmosphere), 3 plant compartments (AGP – aboveground plant; BGP – belowground plant; and FRUIT – fruit) and 2 atmosphere compartments (DATM – diffusive atmosphere; and TATM – turbulent atmosphere). In addition, there is also a sink compartment. The sink compartment is used to represent losses of ^{14}C from the system, including both loss of plant material as a result of harvesting and also ^{14}C in the turbulent atmosphere carried away from the area of interest by diffusion and air movement. The model is able to accept the whole range of source terms that SSM might need to apply to it. At present, the processes within the model are considered on an annual timescale, making it more suited to the assessment of longer-term releases, though the plant biomass can be static or dynamically modeled, the latter allowing for the potential of isotopic dilution in plant matter due to new growth.

As with the models reviewed, a specific activity approach has been adopted for the uptake of plant ^{14}C. The plant is assumed to take up 99% of its carbon via photosynthesis, with 1% coming from root uptake. Although the atmosphere is separated into 2 compartments, it is assumed that the aboveground portion of the plant grows inside the diffuse part of the atmosphere only. SSPAM^{14}C's soil submodel is derived from the RothC model (Coleman and Jenkinson 2005). This model evolved from a model developed to understand carbon turnover in an agricultural soil in the 1970s, using empirical data from extensive field experiments at Rothamsted, UK (Jenkinson and Rayner 1977). Further details of the mathematical model are given in Limer et al. (2013).

Imperial College Experiments

In the 1990s, the UK Ministry of Agriculture, Fisheries and Food (MAFF) funded a study of the assimilation of a selection of radionuclides, including ^{14}C, following atmospheric discharges. Experiments in a wind tunnel were performed to investigate the uptake of these radionuclides into a range of crop types. For the ^{14}C experiments, the atmospheric and plant concentrations were measured in 3 crops: cabbage, potatoes, and broad beans. The details of these experiments are given in Tucker and Shaw (1997). The data from the potato experiment was used as input for analyses by the IAEA EMRAS ^{14}C and tritium working group (IAEA 2008). In the present study, data relating to the cabbage experiment was used to test SSPAM^{14}C. Figure 3 shows the measured atmospheric profile of injected ^{14}C and Figure 4, the measured concentrations of ^{14}C in the various cabbage plant components (leaves, stem, and roots) of one of the replicates (C3). It is the atmospheric profile shown here that SSPAM^{14}C has been applied to in the following section.

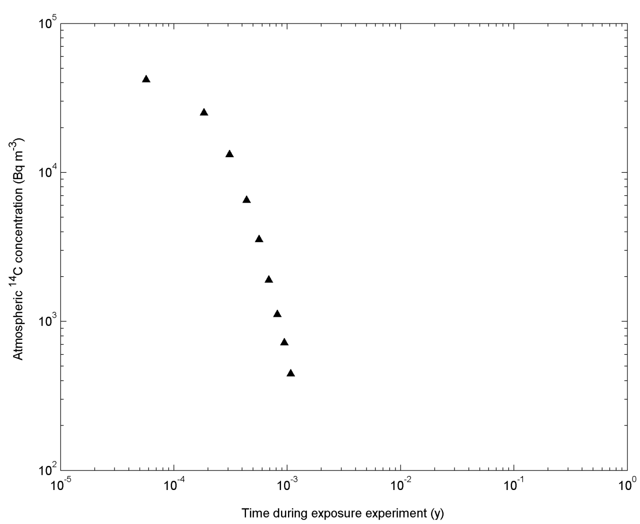

Figure 3 Measured ^{14}C profile in the atmosphere for the C3 cabbage replicate of the Imperial College experiment.

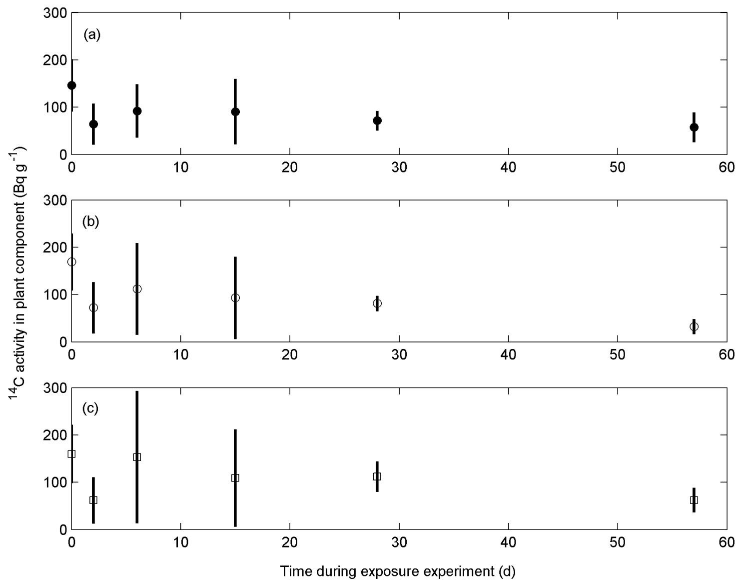

Figure 4 Measured ^{14}C activity concentration in the plant components for the cabbage in C3 replicate exposure (Bq g^{-1}): (a) leaves; (b) stems; and (c) roots. The data points are the means, with the vertical lines representing 1 standard deviation.

RESULTS

In the application of SSPAM^{14}C to the C3 cabbage data, the area of the model was constrained to that of the wind tunnel, and the concentration of ^{14}C in the turbulent atmospheric compartment (TATM) was forced to follow a curve fitted to the measured ^{14}C profile time series (Figure 3). In the initial application, it was assumed that 1% of the plant carbon is obtained from root uptake. As can be seen in Figure 5a, while this led to a reasonable estimation of the aboveground plant ^{14}C concentration (AGP), SSPAM^{14}C grossly underestimated the belowground plant ^{14}C concentrations (BGP). Increasing the proportion of plant C obtained directly from the roots to 10% (as proposed by Livingston and Beall 1934) improves the model fit (Figure 5b), but there is still a significant underestimation as compared the experimental data. Other factors that might affect the calculated BGP ^{14}C concentration, such as the translocation rate between the AGP and BGP compartments and the respiration rate of the BGP, were considered in additional sensitivity calculations but had a lesser impact than the assumed amount of root uptake of carbon.

DISCUSSION

SSPAM^{14}C is a model that will provide SSM with an independent means to assess potential impacts associated with ^{14}C releases to terrestrial environments, from a range of sources. Although the model is still under development, initial tests against experimental data have shown the model is able to recreate aspects of a real system, in particular the aboveground vegetation concentration of ^{14}C. In the future, consideration may be given as to whether or not the aboveground plant component need be discretized further, and whether the soil aspect of the model could be simplified. However, there is an outstanding need for a comprehensive data set that permits validation of all aspects of the model. Further experimental work, such as the ongoing work funded by the UK Nuclear Decommissioning Authority Radioactive Waste Management Directorate (Atkinson et al. 2011), is anticipated to consider the whole soil-plant-atmosphere system, with a focus on belowground releases of ^{14}C-labeled

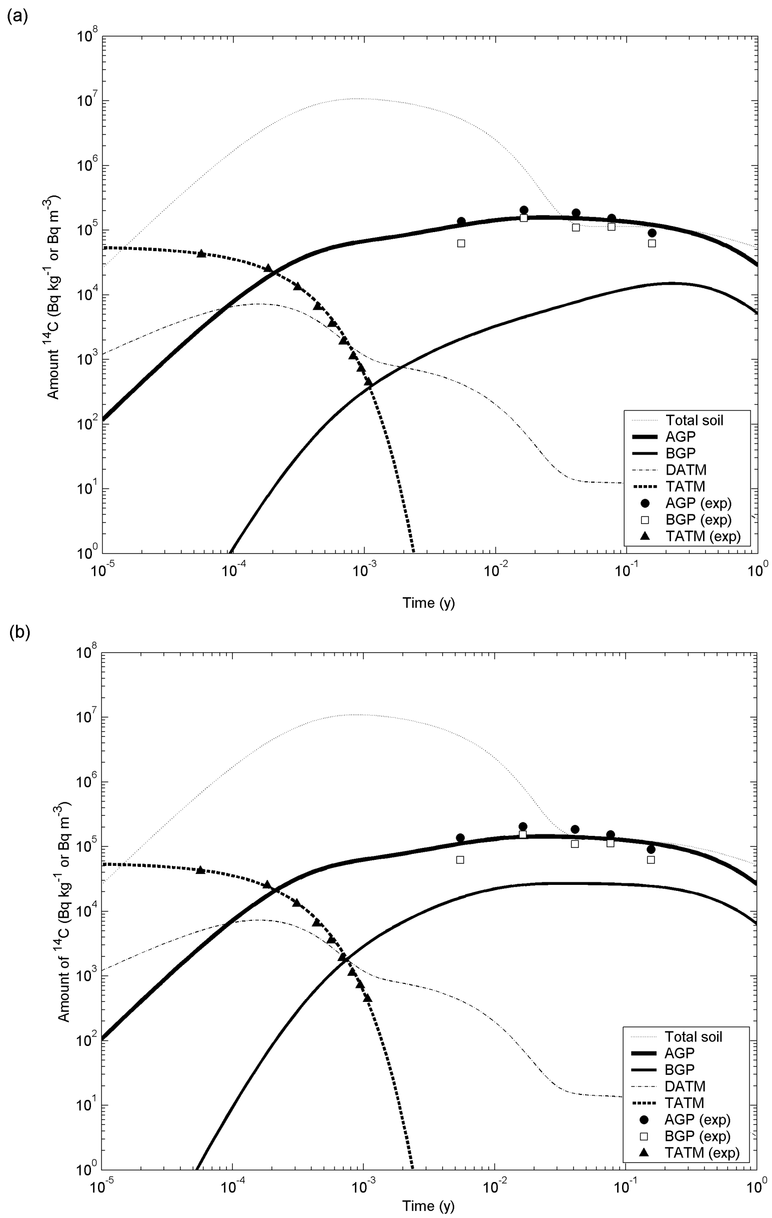

Figure 5 Application of SSPAM^{14}C to the C3 cabbage experiment replicate. (a) 1% of plant carbon obtained via root uptake. (b) 10% of plant carbon obtained via root uptake. The variation in the measured ^{14}C concentrations in plant components is shown in Figure 4.

gas. Other organizations, such as IRSN, have also recently undertaken field measurements of ^{14}C in terrestrial ecosystems following atmospheric discharges (Aulagnier et al. 2012).

ACKNOWLEDGMENTS

This research was funded by Swedish Radiation Safety Authority (SSM).

REFERENCES

Albrecht A. 2010. Les équations du modèle de transfert du carbone-14 (^{14}C) dans la biosphère (AquaC_14) et leur intégration dans le code "Modèle Management, MoM"; Note technique. Report number: C.NT.AS-TR.10.0052.A, ANDRA, Châtenay-Malabry.

Albrecht A, Miquel S. 2010. Extension of sensitivity and uncertainty analysis for long term dose assessment of high level nuclear waste disposal sites to uncertainties in the human behaviour. *Journal of Environmental Radioactivity* 101(1):55–67.

Aquilonius K, Hallberg B. 2005. Process-oriented dose assessment model for ^{14}C due to releases during normal operation of a nuclear power plant. *Journal of Environmental Radioactivity* 82(3):267–83.

Atkinson B, Meredith W, Snape C, Steven M, Shaw G. 2011. Experimental and modelling studies of carbon-14 behaviour in the biosphere: diffusion and oxidation of isotopically labelled methane ($^{13}CH_4$) in laboratory soil column experiments. NDA Radioactive Waste Management Directorate, report no. Serco/Nott/e.4041/002 Issue 1.

Aulagnier C, Le Dizès S, Maro D, Hérbert D, Lardy R, Martin R, Gonze M-A. 2012. Modelling the transfer of ^{14}C from the atmosphere to grass: a case study in a grass field near AREVA-NC La Hague. *Journal of Environmental Radioactivity* 112:52–9.

Avila R, Pröhl G. 2008. Models used in the SFR 1 SAR-08 and KBS-3H safety assessments for calculation of C-14 doses, SKB Rapport R-08-16.

Bush RP, White IF, Smith GM. 1984. Carbon-14 waste management. CEC, Euratom Report EUR-8749.

Canadian Standards Association (CSA). 2008. Guidelines for calculating derived release limits for radioactive material in airborne and liquid effluents for normal operations of nuclear facilities. CSA Standard N288.1-08. Toronto, Canada.

Coleman K, Jenkinson DS. 2005. ROTHC-26.3 a model for the turnover of carbon in soil. IACR – Rothamsted, Harpenden, Herts. November 1999 issue (modified April 2005).

Hjerpe T, Ikonen ATK, Broed R. 2010. Biosphere assessment report 2009. A Posiva Oy report, 2010-03, March 2010.

International Atomic Energy Agency (IAEA). 2008. *The Potato Scenario, Final Report*. EMRAS Tritium/^{14}C Working Group, September 2008. Vienna: IAEA.

Jenkinson DS, Rayner JH. 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. *Soil Science* 123:298–305.

Keum D-K, Jun I, Lim K-M, Choi Y-H, Lee C-W. 2008. Predictive model for the ^{14}C radioactivity in a plant following an exposure to airborne $^{14}CO_2$ gas. *Journal of Environmental Radioactivity* 99(11):1756–63.

Le Dizès S, Maro D, Hébert D, Gonze M-A, Aulagnier C. 2012. TOCATTA: a dynamic transfer model of ^{14}C from the atmosphere to soil-plant systems. *Journal of Environmental Radioactivity* 105(1):48–59.

Le Mer J, Roger P. 2001. Production, oxidation, emission and consumption of methane by soils: a review. *European Journal of Soil Biology* 37(1):25–50.

Limer L, Smith G, Thorne M. 2010. Disposal of graphite: a modelling exercise to determine acceptable release rates to the biosphere. A study for the Nuclear Decommissioning Authority, Radioactive Waste Management Division, QRS-1454A-1, Version 2.2.

Limer LMC, Thorne MC, Towler GH. 2011a. Assessment calculations for C-14 labelled gas for the LLWR 2011 ESC. Quintessa Limited report to LLWR Limited QRS-1443Z-1, Version 4.0, April 2011.

Limer LMC, Thorne MC, Cummings R. 2011b. Consideration of canopy structure in modelling ^{14}C-labelled gas behaviour in the biosphere for human dose assessments. *Radioprotection* 46(6):S409–S415.

Limer LMC, Smith K, Albrecht A, Marang L, Norris S, Smith GM, Thorne MC, Xu S. 2012. C-14 long-term dose assessment: data review, scenario development, and model comparison. SSM report 2012:47. Strålsäkerhetsmyndigheten, Stockholm.

Limer L, Klos R, Shaw G, Walke R. 2013. Terrestrial biosphere modeling of ^{14}C research, final report. A Limer Scientific Consulting Limited report for The Swedish Radiation Safety Authority (SSM). SSM report 2013:20. Strålsäkerhetsmyndigheten, Stockholm.

Livingston BE, Beall R. 1934. The soil as direct source of carbon dioxide for ordinary plants. *Plant Physiology* 9(2):237–59.

Magnusson Å, Strenström K, Aronsson P-O. 2008. ^{14}C in spent ion-exchange resins and process water from nuclear reactors: a method for quantitative determination of organic and inorganic fractions. *Journal of Radioanalytical and Nuclear Chemistry* 275(2):261–73.

Maul PR, Watson CE, Thorne MC. 2005. Probabilistic modelling of C-14 and H-3 uptake by crops and animals. Quintessa report to the Food Standards Agency QRS 1264A-1, Version 3.0, Henley-on-Thames, UK.

Monsi M, Saeki T. 2005. On the factor of light in plant communities and its importance for matter production. *Annals of Botany* 95(3):549–67.

National Council on Radiation Protection (NCRP). 1985. Carbon-14 in the environment. National Council on Radiation Protection and Measurements. NCRP report no 81, USA.

Sheppard MI, Sheppard SC, Amiro BD. 1991. Mobility and plant uptake of inorganic ^{14}C and ^{14}C-labelled PCB in soils of high and low retention. *Health Physics* 61(4):481–92.

Sheppard SC, Ciffroy P, Siclet F, Damois C, Sheppard MI, Stephenson M. 2006a. Conceptual approaches for the development of dynamic specific activity models of ^{14}C transfer from surface water to humans. *Journal* *of Environmental Radioactivity* 87(1):32–51.

Sheppard SC, Sheppard MI, Siclet F. 2006b. Parameterization of a dynamic specific activity model of ^{14}C transfer from surface water to humans. *Journal of Environmental Radioactivity* 87(1):15–31.

Smith GM, Robinson PC, Stenhouse MJ. 1994. C-14 food chain modelling following release to atmosphere. Intera report to the Ministry of Agriculture, Fisheries and Foods IE3725-1, Version 3, Henley-on-Thames, UK.

Tani T, Arai R, Nozoe S, Tako Y, Takahashi T, Nakamura Y. 2011. Development of a dynamic transfer model of ^{14}C from the atmosphere to rice plants. *Journal of Environmental Radioactivity* 102(4):340–7.

Thomson G, Miller A, Smith G, Jackson D. 2008. Radionuclide release calculations for SAR-08. Swedish Nuclear Fuel and Waste Management Company, SKB Report R-08-14. Stockholm.

Thorne MC. 2005. Development of increased understanding of potential radiological impacts of radioactive gases from a deep geological repository: review of FSA and Nirex models and associated scoping calculations. Mike Thorne and Associates Limited report to UK Nirex Limited MTA/P0011b/2005-5: Issue 2, November 2005.

Thorne MC, MacKenzie J. 2005. The treatment of waste-derived gas in the biosphere in Nirex safety and performance assessments. Quintessa Limited report to UK Nirex Limited QRS-1248A-1, Version 2.0, February 2005.

Thorne MC, Khursheed A, Stansby SJ. 2003. Assessing the radiological impact of radionuclides in sewage sludge when applied to agricultural land: final report. Mike Thorne and Associates report to the Food Standards Agency MTA/P0023/2003-1: Issue 1, Ripponden, UK.

Tucker S, Shaw G. 1997. Quality assured modelling data for $^{14}CO_2$ fixation by crops. IC.CARE/MAFF/REP/C-14/4.0, Imperial College report to the Ministry of Agriculture, Fisheries and Foods, London, UK.

Vuorinen AH, Vapaavuori EM, Lapinjoki S. 1989. Time-course of uptake of dissolved inorganic carbon through roots in light and darkness. *Physiologia Plantarum* 77(1):33–8.

Walker AJ, Otlet RL. 1999. Studies on gaseous species of tritium and carbon-14 in environmental air around nuclear establishments. In: Warwick P, editor. *Environmental Radiochemical Analysis*. Special Publication of the Royal Society of Chemistry, 234. Cambridge: ASC. p 159–69.