EMRAS Tritium/C14 Working Group

THE POTATO SCENARIO

Final Report
September 2008

1. SCENARIO DESCRIPTION

The scenario for ^{14}C transfer in crops is based on unpublished data contained in a PhD thesis from Imperial College, U.K. (Tucker, 1998). The crops investigated were cabbage, beans and potatoes. We decided to base the scenario on potatoes because they are widely used.

Approximately two hundred potato tubers (*Solanum tuberosum* cv. Romano) were placed in dark storage on July 5, 1995 and left to chit (sprout). Some tubers were split to produce sufficient plants to transfer three to each of one hundred pots on August 4, 1995. Some of the plants were later thinned to two per pot. The pots had dimensions 40 x 40 x 40 cm and each was filled with Fison's Levington multi-purpose peat-based compost.

The crops were exposed to $^{14}CO_2$ in the MAFF/CARE wind tunnel. This allowed the exposure to take place under realistic atmospheric boundary layer conditions, while providing adequate containment for the $^{14}CO_2$. The experimental layout given in the scenario description shows four plants in each pot. This was the case for cabbage and beans, but only 2-3 plants per pot were used in the potato experiments. The wind tunnel has the capacity to accommodate thirty pots. Twenty of these constituted the 'fetch' of the canopy and facilitated the build up of a turbulent boundary layer. The remaining ten pots provided the plant material to be sampled as part of the experiment, enabling a maximum of thirty potato plants to be sampled for each exposure (but generally 20 plants in the later development stage).

The potato plants were fumigated with $^{14}CO_2$ for approximately 10 hours within the wind tunnel at six stages of the crop's growth cycle. The schedule of fumigations is given in Table 1, which shows the number of days after sowing at which fumigation occurred (the stage of development) and the fumigation date. Following exposure, one-sixth of the plants in the experimental section were selected at random and sampled immediately to measure the activity concentration of ^{14}C fixed by the crop (harvest H1). The remainder of the crop was transported to a walled garden at Imperial College and sampled a further five times until maturity (harvests H2 to H6) at intervals that varied in frequency according to the age of the crop at fumigation, as given in Table 2.

Information on the ^{14}C air activity concentration as a function of time during each fumigation, the time-integrated ^{14}C air concentrations, and the ranges of temperature and photosynthetically active radiation (PAR) in the tunnel during each experiment are given in Tables 3-5, respectively. The average dry weight of the roots, leaves, stems and tubers in all experiments for every harvest time, and the dry weight fractions for each harvest, are given in the scenario description.

It should be noted that normal development for potatoes requires about 140 days to maturity, which was not available for these experiments. The late chitting and sowing dates meant that the plants were growing later in the season than normal, and were exposed to fall rather than summer weather. It is possible that the tubers were not fully mature at final harvest.

Table 1. Fumigation schedule for experiments in which potato plants were exposed to $^{14}CO_2$

Designation of Experiment	Time of Fumigation (Days after sowing)	Fumigation date
P1	21	Aug 25, 1995
P2	33	Sep 7, 1995
P3	47	Sep 21, 1995
P4	61	Oct 5, 1995
P5	74	Oct 18, 1995
P6	89	Nov 2, 1995

Table 2. Potato sampling schedule

	P1		P2		P3		P4		P5		P6	
	Age*	T**	Age	T	Age	T	Age	T	Age	T	Age	T
H1	21	0	33	0	47	0	61	0	74	0	89	0
H2	31	10	38	5	53	6	65	4	79	5	90	1
H3	38	17	44	11	58	11	72	11	83	9	93	4
H4	48	27	58	25	68	21	83	22	87	13	95	6
H5	72	51	79	46	83	36	90	29	93	19	97	8
H6	97	76	97	64	97	50	97	36	100	26	100	11

* days after sowing ** days after exposure

Table 3. C-14 air concentration above the potatoes

P1		P2		P3		P4		P5		P6	
Time (min)	Air conc (Bq/m3)	Time (min)	Air conc (Bq/m3)	Time (min)	Air conc (Bq/m3)	Time (min)	Air conc (Bq/m3)	Time (min)	Air conc (Bq/m3)	Time (min)	Air conc (Bq/m3)
32	65121	32	47090	31	68339	31	55009	30	57453	30	30450
99	43715	99	29804	100	42376	98	34387	97	36612	96	21067
166	21521	166	16279	167	24373	165	18999	163	19576	162	12966
233	12095	233	8297	236	11749	230	10269	236	9906	228	7152
300	6577	301	4405	303	6361	294	5774	304	5028	295	4086
368	3667	369	2490	371	2983	360.5	3359	370	2858	361	2461
435	2325	438	1393	438	1827	430.5	1686	436	1646	426	1452
501	1460	505	801	504	839	496.5	985	501	954	492	900
569	701	570	565	570	694	567	651	568.5	607	566	507

Table 4. C-14 integrated air concentrations

Experiment	Time-integrated air concentration (MBq m^{-3} min)
P1	9.764
P2	6.983
P3	9.647
P4	8.089
P5	8.307
P6	4.774

Table 5. Temperature and PAR ranges during fumigation

Experiment	Range in Temperature (^{o}C)	Range in PAR (W/m^2)
P1	23 -27	70 - 150
P2	21-26	50 - 160
P3	20-23	40 - 160
P4	19-24	30 -130
P5	19-13	30 - 130
P6	17-20	30 - 130

Modelers were asked to calculate the following:

1) the ^{14}C concentration in the leaves at each sampling time (H1 to H6) for each experiment [Bq/g dry matter (dm)];
2) the carbon concentration in the tubers at final harvest (H6) for each experiment [Bq/g dm]; and
3) the 95% confidence intervals on all predictions.

The full scenario description is given in Appendix A.

2. OBSERVATIONS

2.1 Experimental Data

Average values and standard deviations of the following parameters were collected at each harvest following each fumigation:

- fresh and dry weights of each plant component and of the total plant,
- ^{14}C concentrations on dry and wet weight bases for each plant component and for the total plant, and
- ^{14}C inventories for each component and for the total plant (absolute and as a fraction of plant inventory)

The measured ^{14}C concentrations in the plant leaves at each harvest time for each exposure are given in Table 6. The ^{14}C concentrations in the tubers at final harvest are shown in Table 7.

Table 6. C-14 concentrations in leaves

Age (days)	^{14}C concentration in leaves (Bq/g dm)	Standard deviation in concentration
P1		
21	1126.28	373.88
31	312.68	115.74
38	215.48	55.42
48	224.70	148.77
72	106.04	50.65
97	101.38	38.49
P2		
33	482.90	218.91
38	393.72	187.15
44	482.36	138.56
58	279.77	240.01
79	187.17	119.13
97	47.13	27.44
P3		
47	291.42	213.58
53	307.33	147.54
58	196.77	115.31
68	322.20	88.31
83	176.95	157.47
97	107.55	121.41
P4		
61	361.98	207.07
65	42.58	13.75
72	95.43	78.95
83	191.30	26.68
90	132.30	43.83
97	28.60	Not available
P5		
74	456.58	296.46
79	119.27	87.12
83	89.73	118.62
87	79.33	33.46
93	46.87	29.90
100	55.27	16.97
P6		
89	68.86	37.59
90	65.68	22.31
93	27.40	9.70
95	77.67	51.23
97	26.43	28.48
100	76.10	59.68

Table 7. C-14 concentration in tubers at final harvest

Experiment	Age at fumigation (days)	^{14}C concentration in tubers (Bq/g dm)	Standard deviation in concentration
P1	21	15.20	6.48
P2	33	12.98	9.14
P3	47	224.60	141.28
P4	61	181.45	124.52
P5	74	158.70	56.92
P6	89	43.00	41.15

The standard deviations of the measured ^{14}C activities are quite large, reflecting field variability of leaf properties and illumination, as well as variability in tuber growth rates.

2.2 C-14 Concentrations in Potato Plants

The ^{14}C activity concentrations in potato tissues generally fell after exposure in experiments P1 and P2, but the decrease was not very pronounced. The concentrations in experiments P3 to P6 showed very little reduction with time following exposure. In experiments P3 to P5, the edible tubers possessed the highest concentrations among all the plant tissues, either throughout the time course in the case of P3 and P4, or at final harvest in the case of P5. Table 8 indicates that, for all experiments, the ^{14}C inventory in all plants was conserved up to the final harvest, indicating that any respiratory losses after exposure were negligible. It can therefore be concluded that the reductions in ^{14}C concentrations in plant tissues in the first two to three cohorts of the experiment were solely due to translocation to newly-developing tissues, notably edible tuber tissues, which commenced growth 40 days after sowing, i.e. between exposures P2 and P3. From exposure P3 onwards, the tubers always accounted for the greater part of the total plant ^{14}C inventory and, with tuber biomass exceeding all other tissue biomass by several fold, it is clear that once tuber initiation has begun these edible tissues represent the most important sink for any ^{14}C fixed during a contamination event.

Table 8. Results of single factor ANOVA to determine the significance of the change of total ^{14}C inventory in the total plant from harvest to harvest within each exposure experiment.

Experiment	F value	F critical	P value	Significant Loss?
P1	0.59	2.62	0.71	No
P2	1.7	2.74	0.18	No
P3	0.43	3.03	0.82	No
P4	1.09	2.96	0.41	No
P5	2.52	2.9	0.08	No
P6	0.73	2.96	0.61	No

There was no significant decrease in the rate of photosynthesis between experiments P1 to P6. The leaf concentrations were higher in P1 than P6 due to the much greater export of ^{14}C from the leaves during P6. By P6 H2 (1 day after exposure) 68% of plant ^{14}C had been transported to the tubers. The proportion of the total transfer constituted by transfer to the tubers increased with plant age from 27% at P1 to approximately 95% at P6.

The within-harvest covariance on the fixation rate for the 6 potato experiments was relatively constant at approximately 50%. This may be due to the reduction in the number of plants used in the wind tunnel in the later exposures and the different growth profiles of the potato foliage.

2.3 Relationship Between Tuber Size and ^{14}C Content

As potato tubers are composed mostly of imported carbon, it is reasonable to expect that large tubers import more ^{14}C than small ones in contaminated plants. Oparka (1985) described a linear relationship between tuber size and ^{14}C inventory. This may have some importance for radiological dose assessment because potatoes may be graded by tuber size before consumption e.g. large tubers are used for baking potatoes.

All tubers were weighed and analyzed individually from selected plants. Up to thirty tubers were found on some plants, although only a few of them developed to edible size. In order to reduce the amount of analysis necessary, all tubers which remained undeveloped were homogenized and analyzed as a single sample, which provided an average concentration. The remaining tubers were weighed and analyzed for ^{14}C content individually. Time constraints allowed the tubers from only 26 individual plants to be analyzed in this way. The plants were chosen to give a cross section of exposure timings and plant ages. The number of measured tubers on a plant ranged from 3 to 9 and from 0.02 to 30 g dm.

Only one individual plant from Experiment P1 was investigated in this way. This individual was exposed 21 days after sowing and harvested 79 days later. Tuber initiation took place approximately 11 days after the exposure. At this stage, there was no correlation between tuber size and ^{14}C inventory, which was approximately equal for all tubers. The smallest tuber consequently had the highest concentration (426 Bq g^{-1}). This was 14 times higher than the average tuber concentration of the whole individual. This tuber was only 0.07 g dm (0.44 g fresh weight (fw)) so it would not be eaten.

The plants in experiment P2 were exposed 33 days after planting, at a time when the tubers were starting to develop. Four individuals were analyzed from experiment P2, one from each of the harvests at 11, 25, 46 and 64 days post-exposure. The tubers from the individuals harvested 25 and 64 days after exposure displayed significant ($p < 0.05$) linear correlations between tuber size and ^{14}C inventory. However, the individuals sampled at 11 and 46 days post-exposure did not exhibit such a relationship.

In the individual plant harvested 64 days following exposure, the second largest tuber imported 82 times more ^{14}C than the smallest tuber. The ^{14}C activity concentrations in the larger tubers from this plant did not reflect this difference in ^{14}C content due to dilution with stable carbon. These results are equivocal in that two individuals suggest a linear relationship while two others do not.

2.3.1 Potatoes exposed after tuber initiation: Five individuals were sampled from experiment P3, one from each harvest except H3. Six individuals were sampled from Experiment P4. The significance of the correlation coefficient of a linear fit of tuber size and ^{14}C inventory is shown for each sample in Table 9. With the exception of one individual, the correlation was significant in all cases. The non-significant result may possibly be caused by the proximity of the sampling time to the exposure. The results from these two exposures support Oparka's (1985) observations more strongly than those from Experiments P1 and P2. It is possible that the stronger linear relationships are due to the exposure timing in these experiments. In P1 and P2, the exposures took place before tuber initiation.

The differences in the maximum and minimum tuber ^{14}C contents, divided by the minimum contents, are displayed in the third column of Table 9. The fourth column shows the corresponding concentration factors.

Table 9. Significance of linear fits to ^{14}C inventory against tuber size

Individual taken from	Significance of R value	Maximum Inventory factor	Maximum concentration factor
P3 H1	5%	1884	54
P3 H2	0.1%	65	3
P3 H4	1%	21	3
P3 H5	5%	1643	27
P3 H6	5%	33804	124
P4 H1	Not significant	959	511
P4 H2	1%	178	9.1
P4 H3	1%	40	3
P4 H4	1%	4494	113
P4 H5	0.1%	1544	47
P4 H6	5%	1472	472

The difference in ^{14}C content between tubers on an individual plant varied by a factor of up to 33804. The corresponding concentration factor for this plant was 124. The import of ^{14}C is accompanied by the import of stable carbon, which leads to a reduction in ^{14}C concentration. However, the level of dilution was not sufficient to make the concentrations equal in tubers of all sizes.

With the exception of the sample from P4 H1, the largest differences in ^{14}C concentration occurred at final harvest for Experiments P3 and P4. The concentrations ranged from 2.1 to 256 Bq g^{-1} for the individual sampled from P3 H6 and from 1.24 to 585 Bq g^{-1} for the plant from P4 H6. The average 'pooled' tuber ^{14}C concentrations were 124.7 Bq g^{-1} and 269 Bq g^{-1} for these samples. This indicates that the tuber ^{14}C concentrations in the largest tubers can be approximately double the average measured values.

2.3.2 Potatoes exposed close to senescence: Ten potato plants from experiments P5 and P6 were also analyzed for the ^{14}C content of individual tubers. Only one of the ten plants exhibited a significant relationship between tuber weight and ^{14}C inventory. There were, however, large differences between the amounts of ^{14}C imported into individual tubers. The maximum range of concentrations was from 0.69 Bq g^{-1} to 154 Bq g^{-1} at P5 H5. The 'pooled' average activity concentration for tubers on this plant was 55.7 Bq g^{-1}. Therefore the maximum activity concentration was approximately 3 times greater than the average.

In plants from experiments P5 and P6, one or two tubers constituted large sinks for ^{14}C with very little imported into the other tubers. These tubers were usually (but not exclusively) the largest tubers. This dominance of one or two tubers may have been due to ontogenic effects at this stage of plant development. Additionally, the collapse of the haulm during these two experiments may have favored carbohydrate supply to one or two tubers over the others.

2.3.3 Summary: The relationship between tuber size and ^{14}C content appears to be dependent on the timing of the exposure. The results from exposures carried out before tuber initiation are inconclusive with respect to the assumption of a linear dependence between size and tuber ^{14}C content. They do, however, illustrate that there may be differences between individual tuber ^{14}C contents and concentrations.

Plants exposed during tuber bulking (ie. the period of time during which tubers experience rapid growth) did show a linear relationship. There were very large differences in ^{14}C content and concentration between individual tubers. Large tubers could contain approximately twice the average concentration. The increased import of ^{14}C was not entirely matched by an increase in stable carbon. This could be due to the changing ratio of ^{14}C in the translocated carbon with time.

Plants exposed after the collapse of the haulm exported ^{14}C to one or two dominant tubers. Such tubers could contain up to three times the average concentration of ^{14}C. The implications of these observations are that a critical group may increase its dose from the ingestion of potatoes by eating larger tubers.

2.4 Partition Fractions

The rate of transfer of ^{14}C between plant compartments was not solely dependent on the 'sink demand' but also on the chemical partitioning of the ^{14}C. The initial ^{14}C incorporation in the plants was low for experiments P1 and P6 and higher for P2-P5 (Figure 1). This cannot be explained by the illumination levels or air temperatures in the wind tunnel, which were roughly constant for the first three fumigations and somewhat lower for the last three (Table 5). For P1, the low incorporation is explained by the low leaf area index at this development stage; for P6, both plant senescence and low leaf area index contributed to the low incorporation.

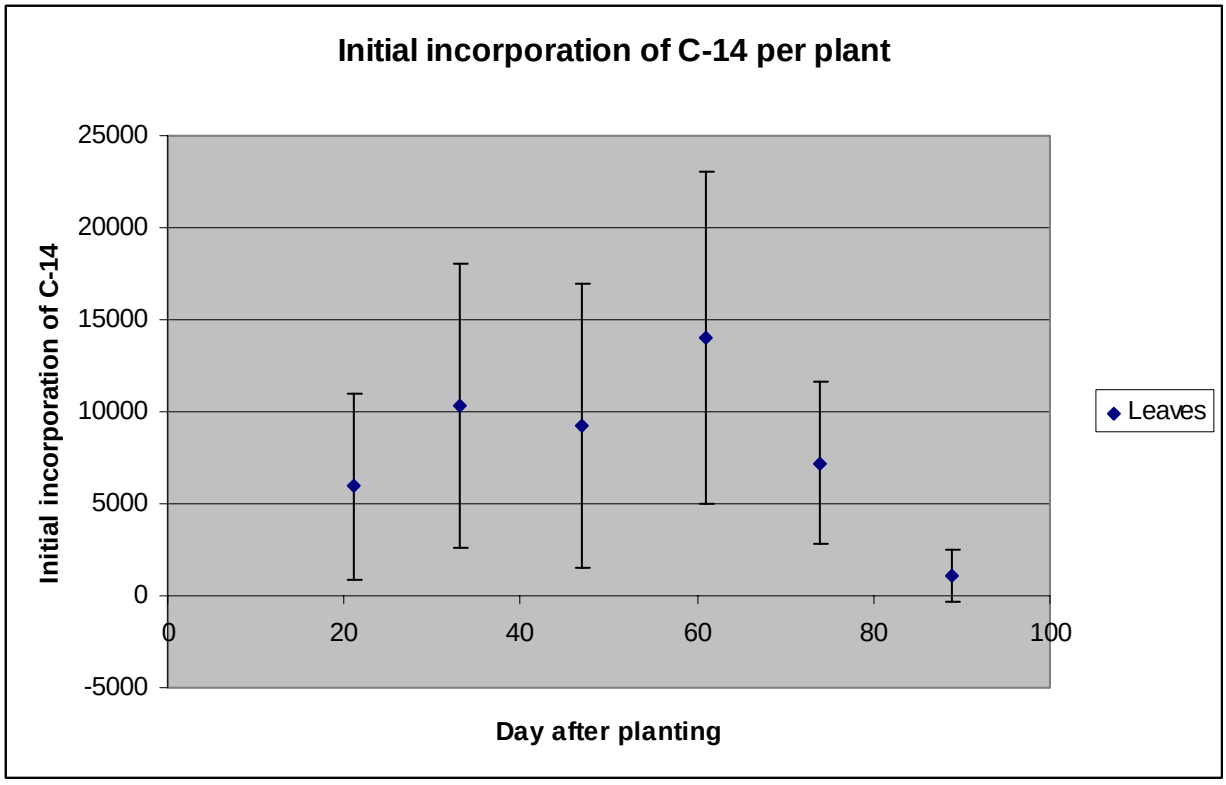

Figure 1. The initial incorporation of ^{14}C per plant

Time-dependent partition fractions for each plant part were calculated from the ^{14}C inventories in leaves, stems, roots and tubers for each fumigation and sampling time. We give an example for leaves in Figure 2. Due to the late seeding, the plants were unable to complete their normal

development by the end of the study, which may explain the high partition fractions for the last fumigation (P6). The initial partition fractions in leaves can also vary substantially depending on genotype and the amount of fertilization (Karvonen and Kleemola, 1995).

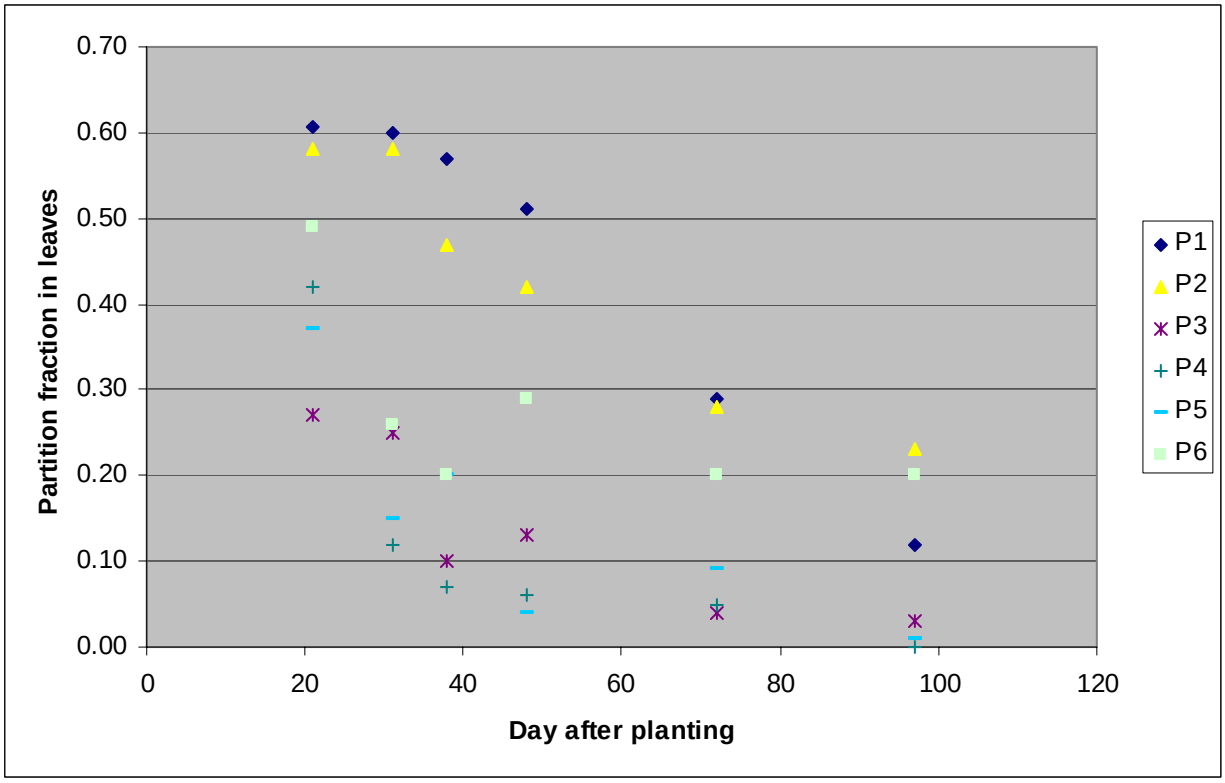

Figure 2. Time evolution of partition fraction in leaves for each fumigation

There was a significant drop in the partition fractions for leaves and stems combined just before final harvest in all fumigations (Figure 3). This reflects a translocation of labile photosynthates to tubers at senescence. This is a physiological process well established in many perennial plants, including potatoes. However, it is included only in very advanced growth models, and not usually in those applied to radiological contamination. Significant translocation also occurs from stems to storage organs at the start of tuber formation. About 20 – 40% of the dry matter in the stems is translocated to the tubers at this time.

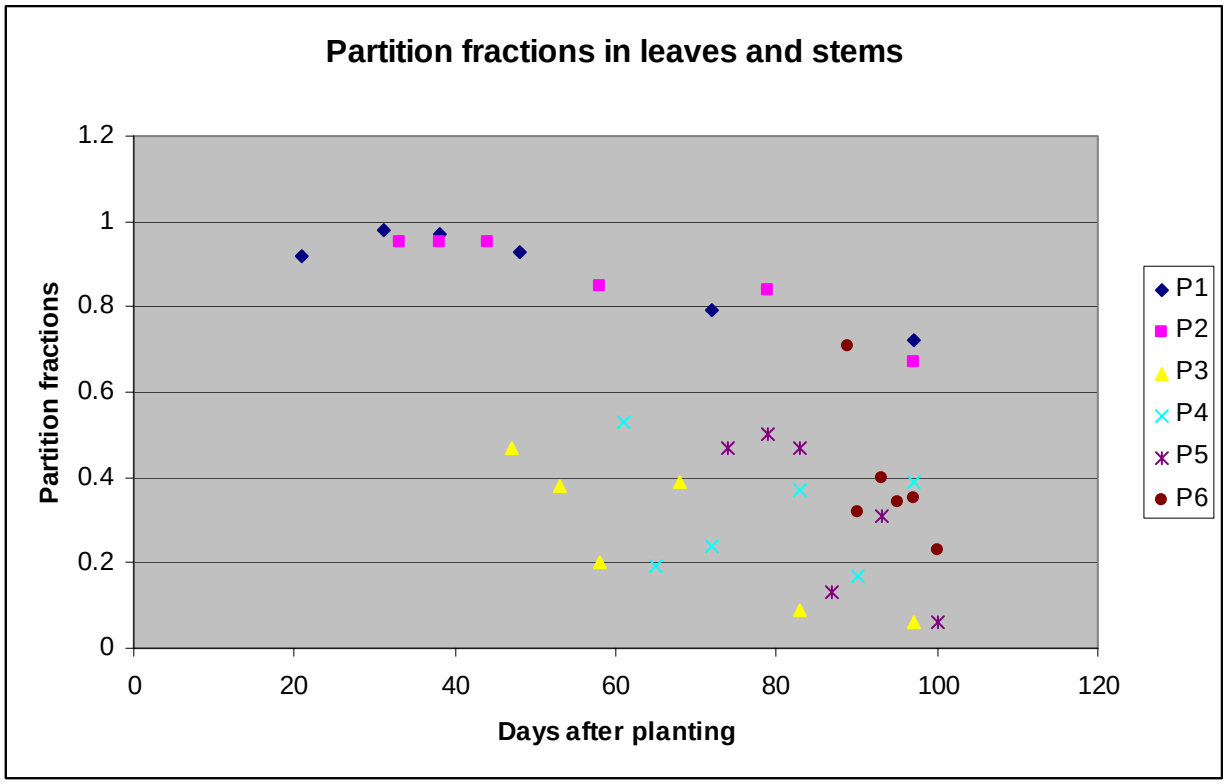

Figure 3. Time evolution of partition fraction in leaves and stems combined for each fumigation

3. MODELING APPROACHES

Four participants submitted results for this scenario (Table 10). The participants from Romania carried out calculations with two models, one simple (Scottish) and the other more complex (WOFOST). All participants treated the scenario as a blind test of their models and submitted results before the observed concentrations were made known to them. However, the participants from Japan submitted revised predictions after the data had been disclosed.

Table 10. Participants in the Potato Scenario

Participant	Affiliation	Model	Designation in the text
F. Siclet	Electricite de France, France	OURSON	EDF
P. Kennedy	Food Standards Agency, UK	PRISM3	FSA
A. Melintescu and D. Galeriu	National Institute for Physics and Nuclear Engineering, Romania	WOFOST Scottish	WOFOST Scottish
S. Uchida et al. [a]	National Institute of Radiological Sciences, University of Kyoto, and Yfirst Inc., Japan	MOGRA	UTTY UTTY revised

[a] S. Uchida, H. Takeda and K. Tagami (NIRS); T. Takahashi (Kyoto Univ.); and K. Yamamoto (Yfirst Inc.)

The OURSON model is a dynamic model primarily developed to evaluate radionuclide concentrations in the aquatic and terrestrial environments following liquid discharges. It assumes that the incorporation of ^{14}C in the plant results from photosynthetic carbon assimilation and that translocation occurs between the leaves, where photosynthesis takes place,

and the storage organs. The net photosynthetic carbon assimilation rate, which is a function of leaf biomass, corresponds to the total growth rate of the plant. The allocation of photosynthates to different parts of the plant depends on the growth stage.

PRISM3 is a dynamic compartment model that considers biological and environmental compartments, including separate compartments for soil water and soil organic matter. It is designed to be conservative for use in regulatory assessments. The external parts of the plant are not explicitly represented, as all sources are considered to be gaseous. Root storage is not considered due to rapid redistribution of ^{14}C.

WOFOST is a model developed by the Wageningen School in The Netherlands for plant growth. The photosynthesis sub-model in WOFOST, with default parameter values for potatoes, was used to predict time-dependent photosynthetically active radiation (PAR), leaf area index (LAI), and maximum leaf photosynthesis rate.

The Scottish model (Kooman and Spitters, 1995) considers dry matter production only, according to the following equation:

$$\Delta W = L_e \, PAR \, L_i$$

where ΔW is the dry mass increment (g m^{-2} d^{-1});
L_e is the light use efficiency (g/MJ);
PAR is the incoming photosynthetically active radiation (MJ m^{-2} d^{-1}); and
L_i is the light interception, which depends on the leaf area index (LAI) and the extinction coefficient for PAR

The initial partition for leaves differs by a factor 2 for the two genotypes considered by the WOFOST and Scottish models.

The UTTY model is a dynamic compartment model that was developed using the MOGRA tool (Migration Of GRound Additions). It considers two organic compartments (stem-leaf-root and tuber), one inorganic compartment (the whole plant) and two environmental compartments (air and soil). This model is essentially the same as the UTTY model used in the EMRAS rice scenario, with the tuber compartment replacing the rice grain compartment and the plant growth model modified to reflect potatoes.

Full descriptions of all the models are given in Appendix B.

4. RESULTS

4.1 C-14 Concentrations in Leaves

The predictions of ^{14}C concentrations in leaves following the P1 fumigation are shown in Figure 4. Generally, the WOFOST and Scottish models underestimate the data, although by less than a factor of 5. The remaining models all overestimate the observations, by up to a factor of 5 for FSA, a factor between 3 and 6 for EDF, and up to a factor of 20 for UTTY. The predictions of UTTY revised are better, overestimating the observations by less than a factor of 4.

The results for experiment P2 are shown in Figure 5. The WOFOST and Scottish models underestimate the data for the first five samplings by up to a factor of 5, but overestimate H6 by a similar margin. FSA overestimates at all sampling times but by a significant amount (a factor of 25) only for H6. EDF overestimates by a factor of 11 at H1, by a factor of 6 at H6, and by a factor close to 1 at other sampling times. UTTY overestimates at H1 by a factor of 17, at

intermediate times by a factor of about 7, and at H6 by a factor of 20. The predictions of UTTY revised are better, overestimating by a factor between 1 and 3.

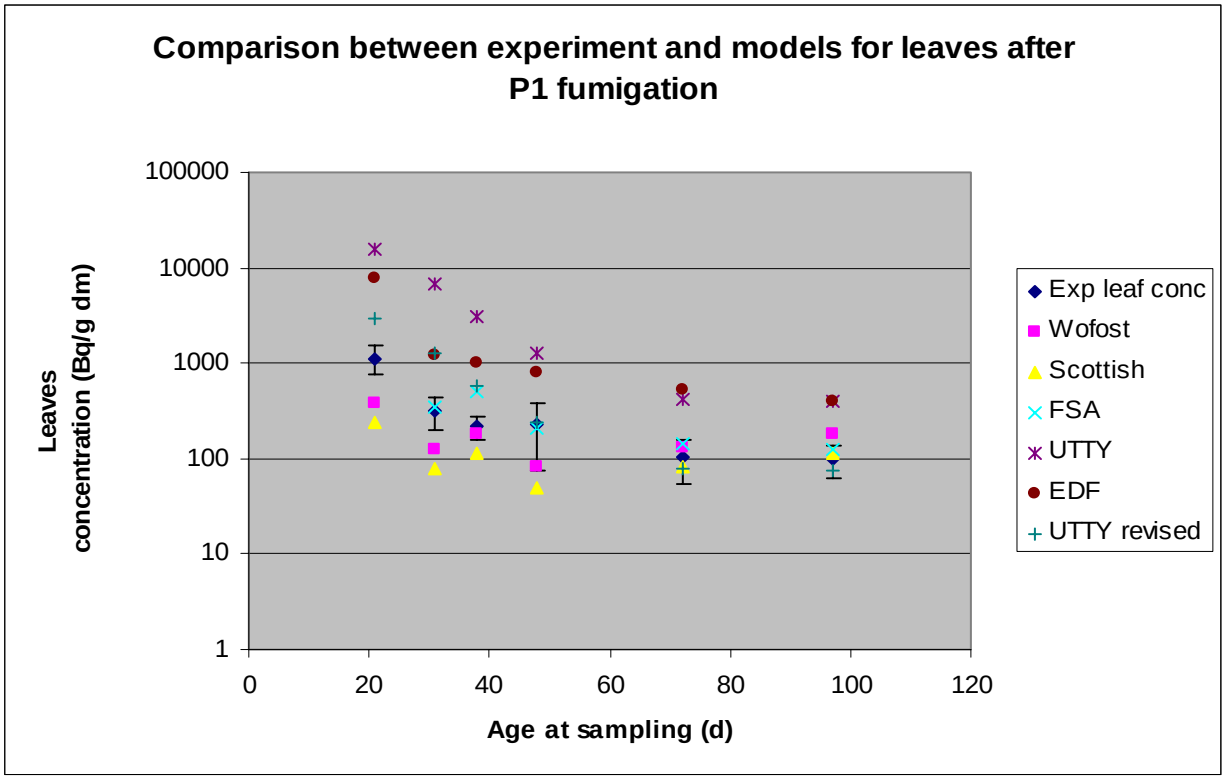

Figure 4. Comparison between predictions and observations for the ^{14}C concentration in leaves following the P1 fumigation

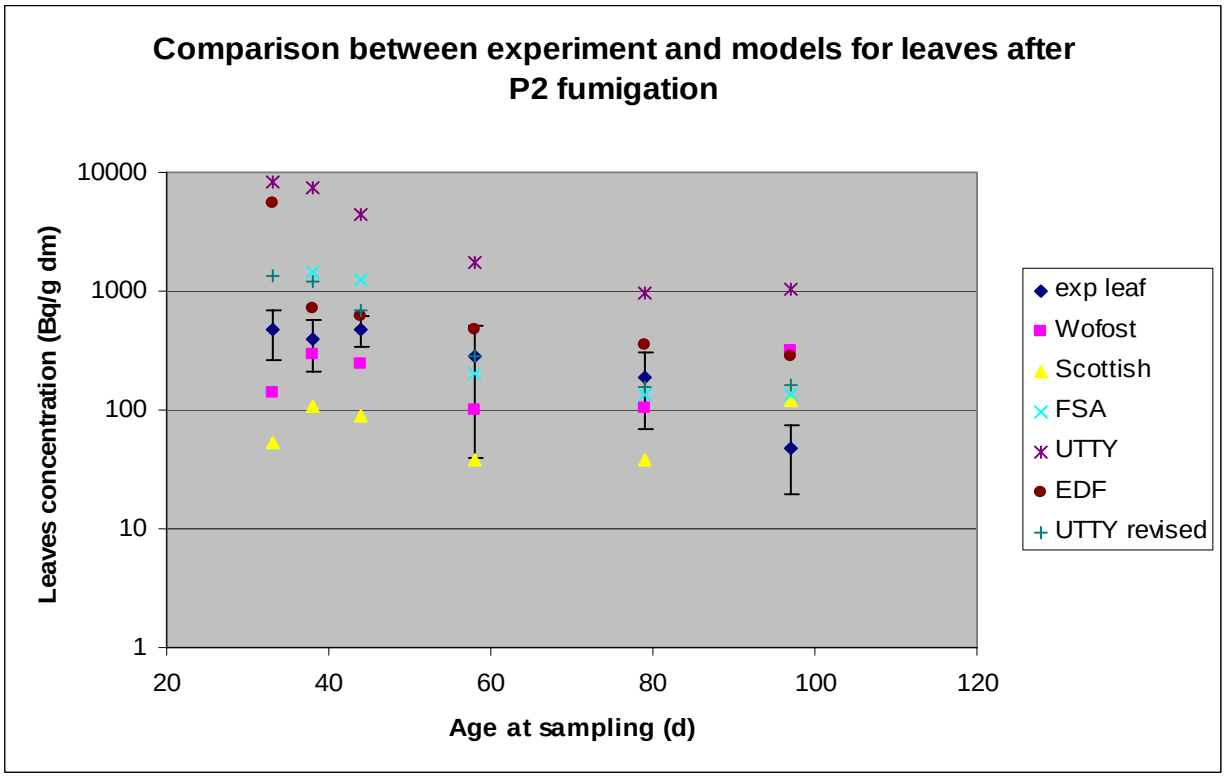

Figure 5. Comparison between predictions and observations for the ^{14}C concentration in leaves following the P2 fumigation

For the P3 fumigation, the WOFOST and Scottish models overestimate the observations by a factor less than 6, except for the last sampling where the overestimate increases to a factor greater than 10 (Figure 3). The large overestimation for H6 is believed to be due to the use of the green leaf mass reported in the scenario description and the neglect of the contaminated dead leaves. The results for FSA are similar to those of WOFOST and Scottish. EDF overestimates by as much as a factor of 3, UTTY by a factor between 10 and 24, and UTTY revised by a factor less than 2.

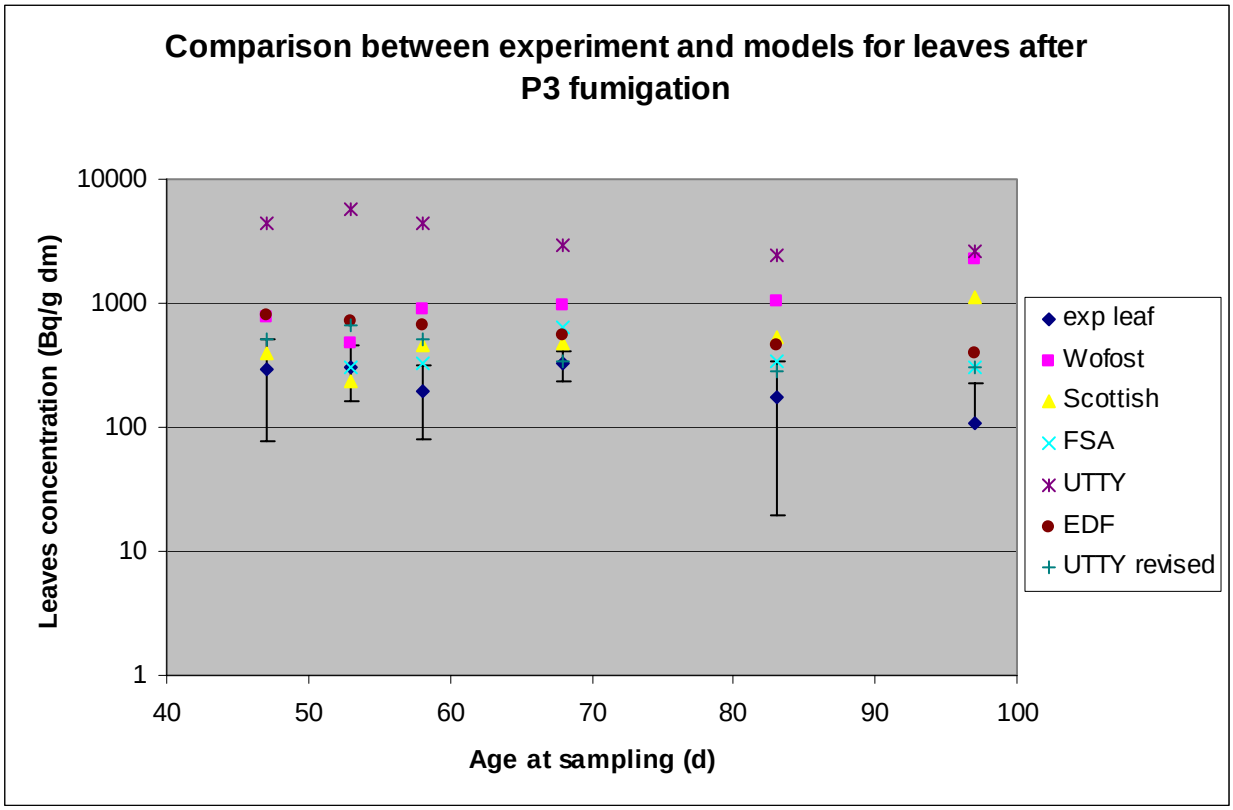

Figure 6. Comparison between predictions and observations for the ^{14}C concentration in leaves following the P3 fumigation

For the P4 fumigation (Figure 7), WOFOST with its default parameter values does not predict any ^{14}C in the leaves. The Scottish model underestimates at H1 by a factor of 10, and at H6 by a factor 40, but the predictions at intermediate times are quite good. The FSA predictions agree with the observations when uncertainties are taken into account with the exception of the last sampling, when it overestimates by a factor near 30. EDF overestimates by a factor between 1 and 11, UTTY by a factor between 10 and 80, and UTTY revised by a factor between 1 and 5. All models significantly overestimate the observed concentration at H6.

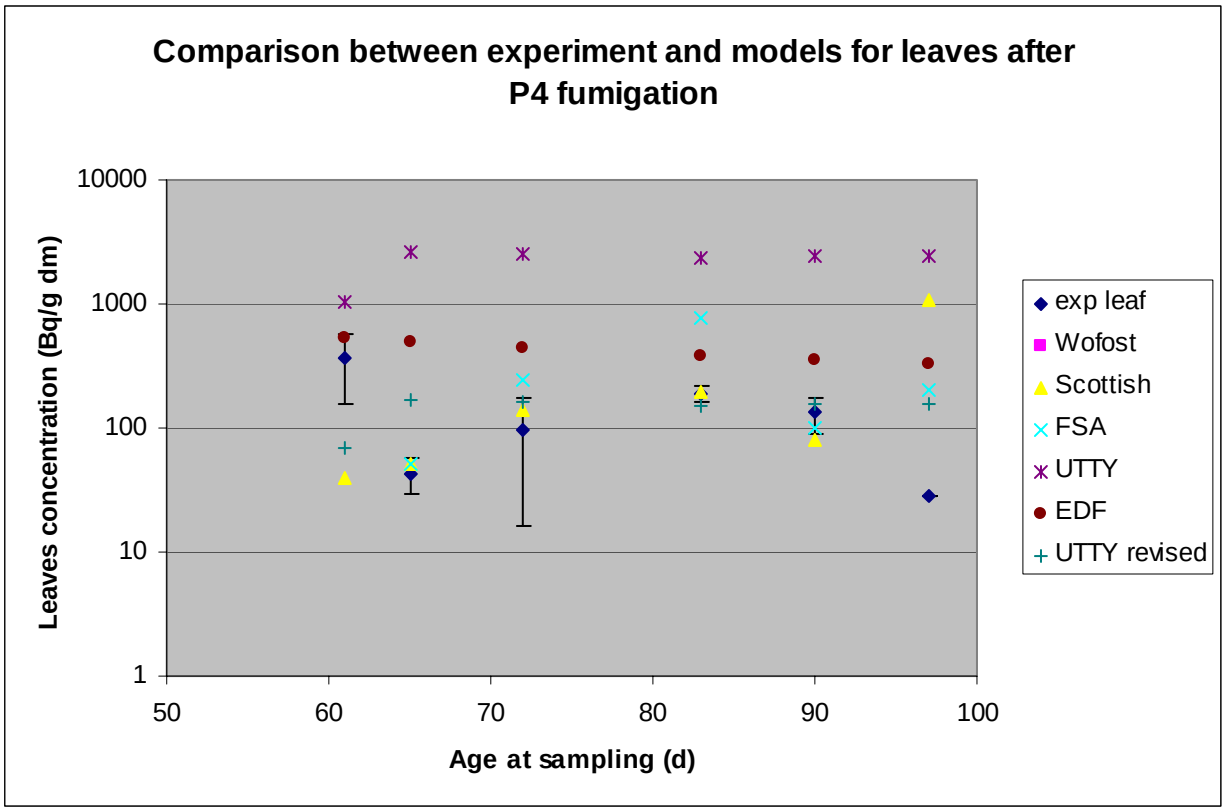

Figure 7. Comparison between predictions and observations for the ^{14}C concentration in leaves following the P4 fumigation

For the P5 fumigation (Figure 8), WOFOST predicts that the ^{14}C concentration in the leaves is zero. The Scottish model underestimates the observations, by a factor of 5 at the beginning of the experiment and by smaller factors at later times. FSA also overpredicts, by a factor of 10 at H1 and a factor of 50 at H6. EDF reproduces the observed concentration well at H1 but overestimates by a factor of 7 at the other sampling times. UTTY and UTTY revised both underestimate by a factor 10 at H1 and then predict no ^{14}C in the leaves.

For the P6 fumigation (Figure 9), WOFOST, UTTY and UTTY revised do not predict any ^{14}C in the leaves. The Scottish model underestimates the data by a factor less than 2. The FSA model also underestimates by up to a factor of 6. The EDF model overestimates the ^{14}C concentrations by a factor between 2 and 7.

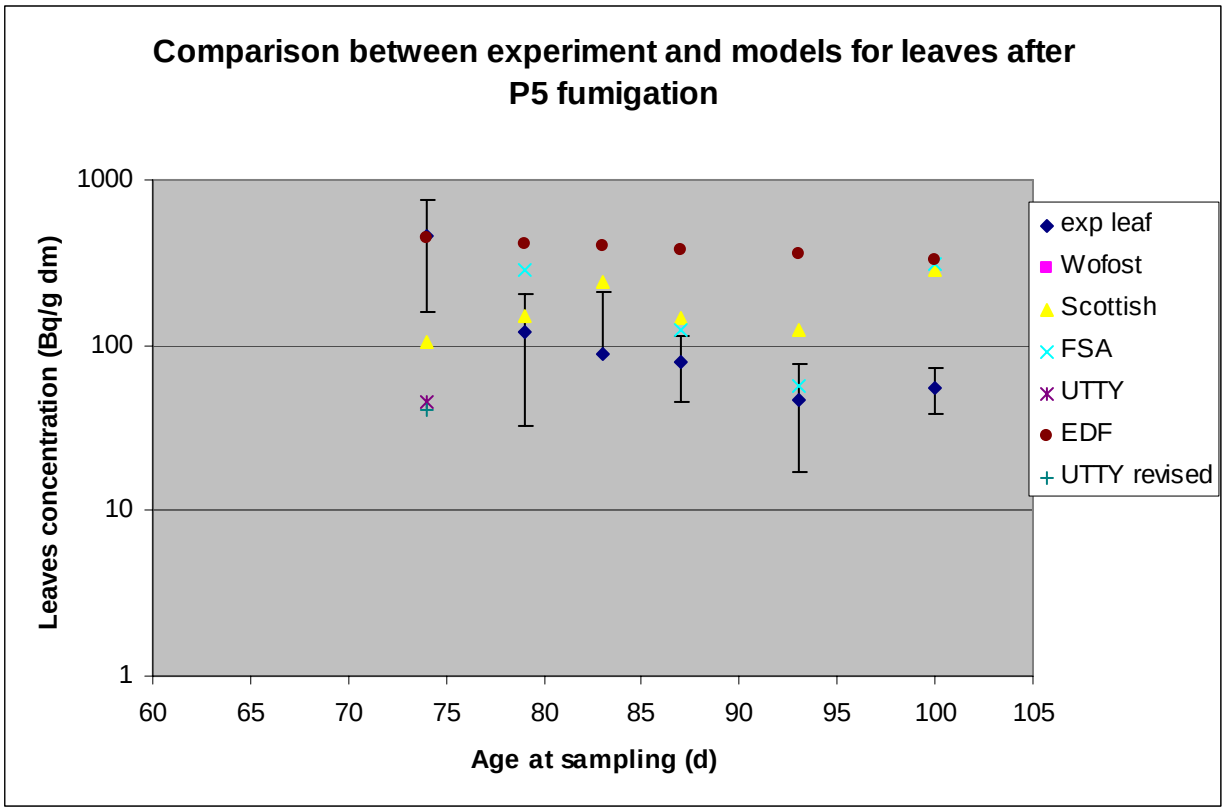

Figure 8. Comparison between predictions and observations for the ^{14}C concentration in leaves following the P5 fumigation

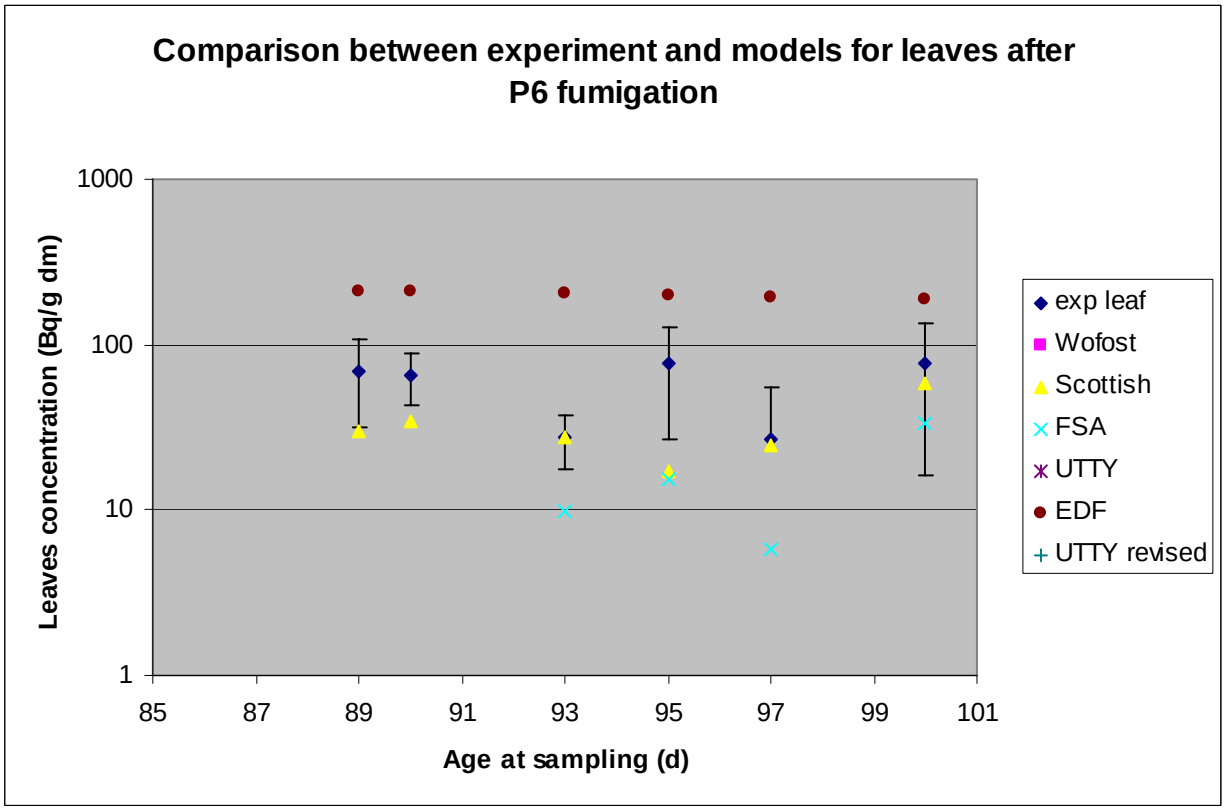

Figure 9. Comparison between predictions and observations for the ^{14}C concentration in leaves following the P6 fumigation

4.2 Discussion of Predicted Leaf Concentrations

Considering the uncertainty in the experimental data (Tables 6 and 7) and the complex processes of partition and translocation involved in this scenario, the predictions cannot be expected to agree with the observations to better than a factor 5. All the models tend to substantially overestimate the leaf concentration at the last sampling point, close to senescence, when translocation from leaves to tubers is ignored by the models.

Generally, UTTY significantly overestimated the ^{14}C concentration in leaves. They hypothesize that, in their model, the ^{14}C in the plant inorganic compartment included some residual ^{14}C picked up after the 10-h exposure itself, implying that each part of the potato plant (stem, leaf and tubers) was effectively exposed for more than 10 hours. C-14 transfer to the inorganic compartment should become zero immediately after the exposure, when the ^{14}C concentration in air drops to zero. The model will be improved in this regard in the future but, to correct the problem for this scenario, additional calculations were carried out with a reduced air concentration, chosen so that the time-integrated ^{14}C amount in the organic compartment reflected the 10-h exposure time. These calculations were submitted as the UTTY revised model, which showed much better performance than the original model. The ratio of the ^{14}C concentration in air during the 10-h exposure to the time-integrated ^{14}C content in the inorganic compartment was different in each experiment because the plant growth rate was different. The improved performance of the UTTY revised model was due to an imposed decrease in the ^{14}C air concentration to which the potatoes were exposed, and not to any change in the conceptual model.

The EDF model overestimated most of the experimental data, by a factor of about 5 on average, perhaps because it does not consider light and temperature effects on the photosynthetic rate, which is set to a maximum value.

In all cases, the FSA model predicted zero concentration in the leaves at the first sampling time, which is not reasonable. FSA has indicated that finite concentrations can be obtained by changing the time of H1 to one day after the start of the exposure. The inference is that the H1 time point was interpreted to be either before or during fumigation in the model runs, suggesting that this is likely a problem of the user interface.

The analysis of ^{14}C dynamics in leaves must start with the initial contamination immediately after fumigation (sampling time H1). Figure 10 shows the predicted to observed ratios for ^{14}C concentration in leaves at this time. The EDF and UTTY models overestimated by a factor of 10 or more, UTTY revised overestimated by a factor of about 2, and WOFOST and the Scottish models underestimated by a factor of about 5. As noted above, FSA predicted zero concentration in leaves at H1, which was not in agreement with observation. The WOFOST model did not predict any ^{14}C concentration in leaves at H1 for the last three experiments. This is explained by an improper choice for the partition fractions that describe the translocation of new photosynthates to the various plant parts for the cultivar assumed in this scenario, as discussed in the full model description (Appendix B).

After the initial day of contamination, the dynamics in leaves depends strongly on translocation (reallocation) of photosynthates to other plant parts – stems, new leaves, roots and tubers. Differences among model predictions can be explained by the different assumptions made with regard to the partition fractions, which depend on the development stage of the plant and the specific genotype.

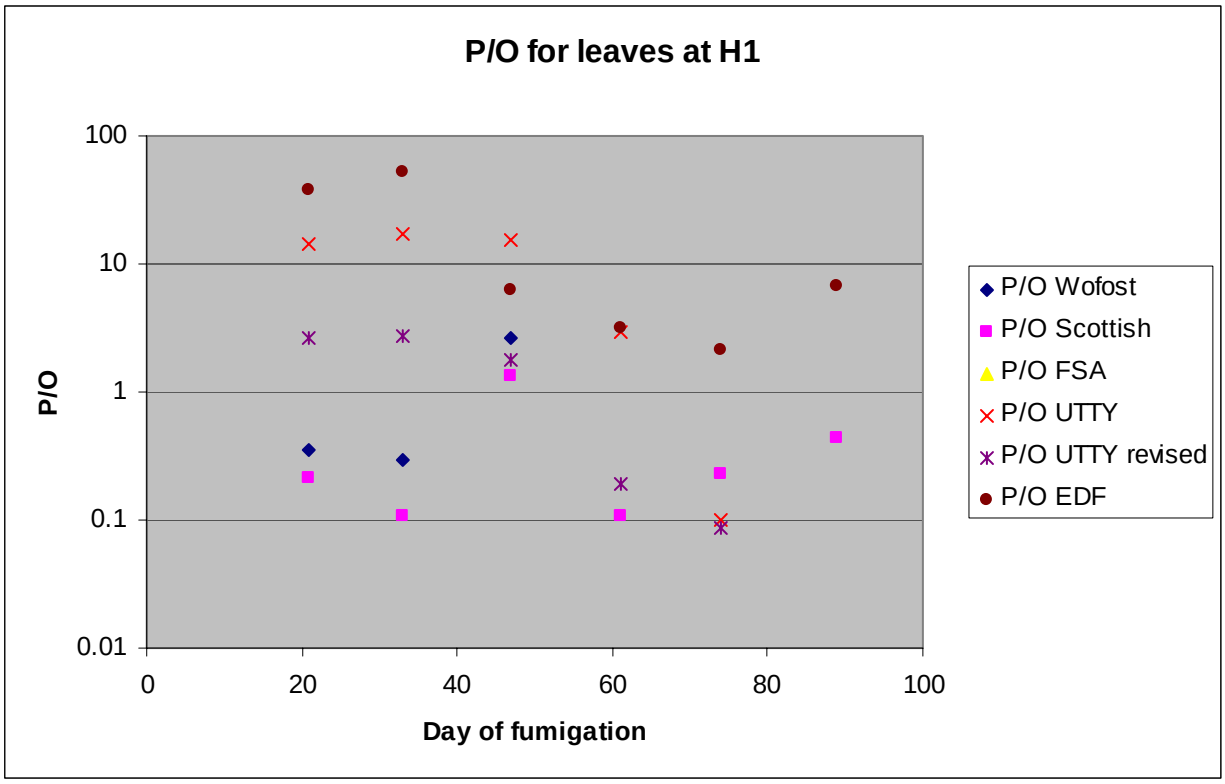

Figure 10. Predicted to observed ratio for C-14 concentration in leaves at the H1 sampling

4.3 C-14 Concentrations in Tubers

The concentrations in the tubers are of greater radiological significance than those in the leaves, since the tubers comprise the edible part of the plant. The best results were given by FSA, where the predictions agreed with the observations to within a factor of 3 for all fumigations (Figure 11). EDF overestimated by up to a factor of 6. UTTY overestimated substantially by a factor between 3 and 68. UTTY revised performed better, but still overestimated by a factor between 1 and 10. The WOFOST and Scottish models did not predict any contamination in tubers for the first fumigation, underestimated for the second fumigation, and overpredicted by a factor of 6 for the last fumigation. For intermediate experiments, the predictions lay within a factor of 2 of the observations.

For all models, the predicted ^{14}C concentrations in the tubers were better than those in the leaves. This may be partially the result of compensatory errors, at least for those models that greatly overpredicted the initial contamination of the potato plant.

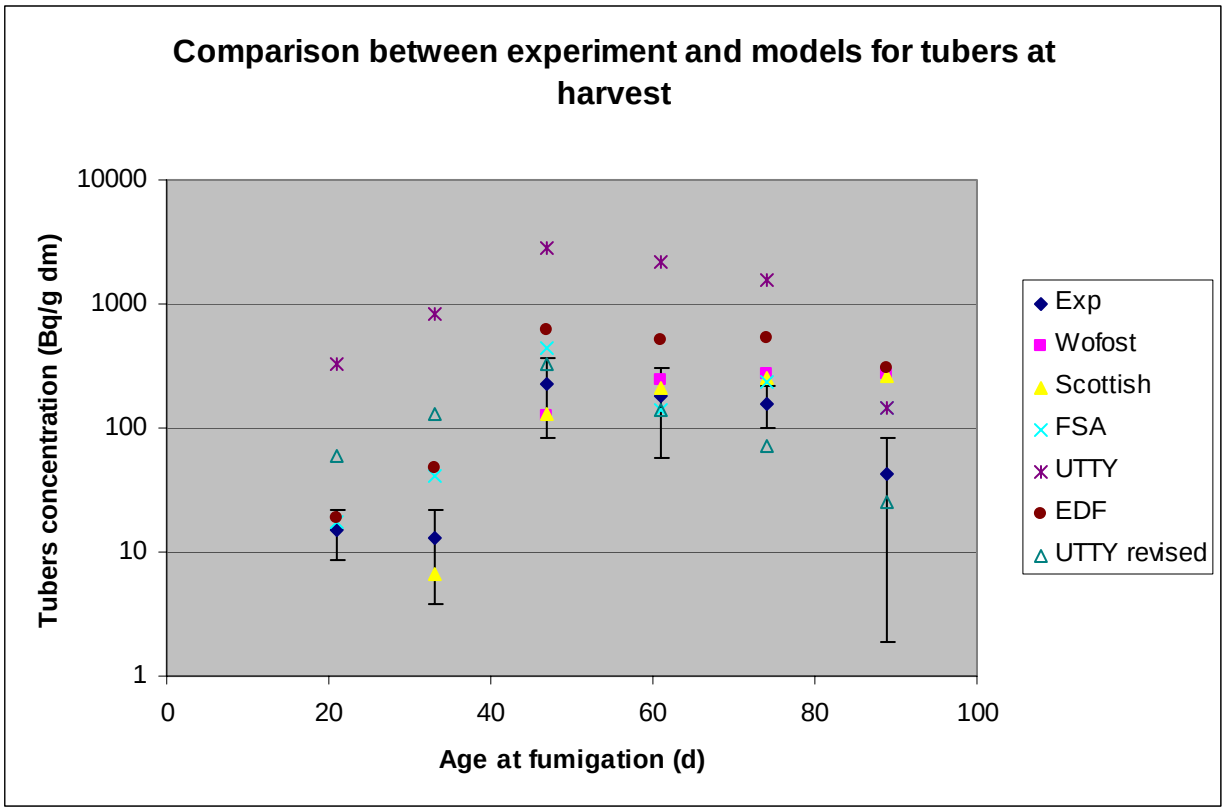

Figure 11. Comparison between predictions and observations of ^{14}C concentrations in tubers at final harvest

5. DISCUSSION AND CONCLUSIONS

The Potato Scenario provided a good test of models that predict ^{14}C concentrations in plants following an acute exposure to ^{14}C in air. The uncertainty in the experimental data was quite large, but this reflects natural conditions because the variability in ^{14}C concentrations in field plants is also large. The main limitations in the data arose from the late seeding (August 4) and the abrupt and early senescence of the plants, which was caused by the onset of autumn weather conditions shortly after exposure. Most models assumed the plants developed normally, which was not the case in the scenario.

The following conclusions can be drawn from the results of this scenario:

- The plant genotype is important in determining ^{14}C concentrations, because the partitioning of new photosynthate to leaves, stems and tubers depends on the cultivar.
- Respiration dynamics is important shortly after fumigation, because the slow respiration rate has a half time of about 2 days.
- Translocation from stems to tubers is also important when the fumigation occurs at the start of tuber formation. There are indications in the data that, at plant senescence, carbon is translocated from leaves and stems to tubers.
- A simple model can be used for the initial incorporation of ^{14}C into the plant, but a process-level model is required to assess partitioning if uncertainties are to be kept relatively low.
- The low rate of ^{14}C incorporation in the plant during the last exposure may have been due to the weather conditions at the time, which were not known for inclusion in the scenario description.
- The relatively good predictions of ^{14}C concentrations in tubers should be analysed to see if they are the result of compensatory errors.

- The large uncertainties in the experimental data make it difficult to draw firm conclusions regarding model performance.

Even though the experimental data on ^{14}C dynamics in leaves are poorly reproduced by most of the models, the predicted concentrations in tubers almost always agree with the observations to better than a factor of 10.

APPENDIX A

Potato Scenario Description

March 2006

At the Vienna EMRAS conference in the fall of 2005, it was decided to initiate a scenario for C-14 transfer in crops based on unpublished data contained in a thesis from Imperial College. The crops investigated were cabbage, beans and potatoes. We decided to start the scenario with potatoes because they are widely used.

Experimental conditions

Approximately two hundred potato tubers (*Solanum tuberosum* cv. Romano) were placed in dark storage on July 5 1995 and left to chit (sprout). Some tubers were split to produce sufficient plants to transfer three to each of one hundred pots on August 4 1995. Some of the plants were later thinned to two per pot. The pots had dimensions 40x40x40 cm and each was filled with Fison's Levington multi-purpose peat-based compost. The plants were cultivated in a walled garden at Imperial College.

The crops were exposed to $^{14}CO_2$ in the MAFF/CARE wind tunnel. This allowed the exposure to take place under realistic atmospheric boundary layer conditions, while providing adequate containment for the $^{14}CO_2$. The experimental layout is shown in Figure A.1, where each pot contains four plants, as in experiments with cabbage and beans. In the potato experiment only 2-3 plants per pot were used.

The wind tunnel has the capacity to accommodate thirty pots. Twenty of these constitute the 'fetch' of the canopy and facilitate the build up of a turbulent boundary layer. The remaining ten pots provided the plant material to be sampled as part of the experiment, enabling a maximum of thirty potato plants to be sampled for each exposure (but generally 20 plants in the later development stage).

The potato plants were fumigated with $^{14}CO_2$ for approximately 10 hours within the wind tunnel at six stages (P1 – P6) of the crop's growth cycle. The schedule of fumigations is summarized in Table A.1, which shows the number of days after sowing at which fumigation occurred (stage of development) and the fumigation date. The date of chitting of this crop was 5th July 1995 and the planting date was 4th August 1995. Following fumigation, samples were taken immediately to measure the activity concentration of ^{14}C fixed by the crop (harvest H1) and the plants were moved outside to the garden. Subsequent samples (H2 to H6) were taken at intervals that varied in number and frequency according to the age of the crop at fumigation, as given in Table A.2.

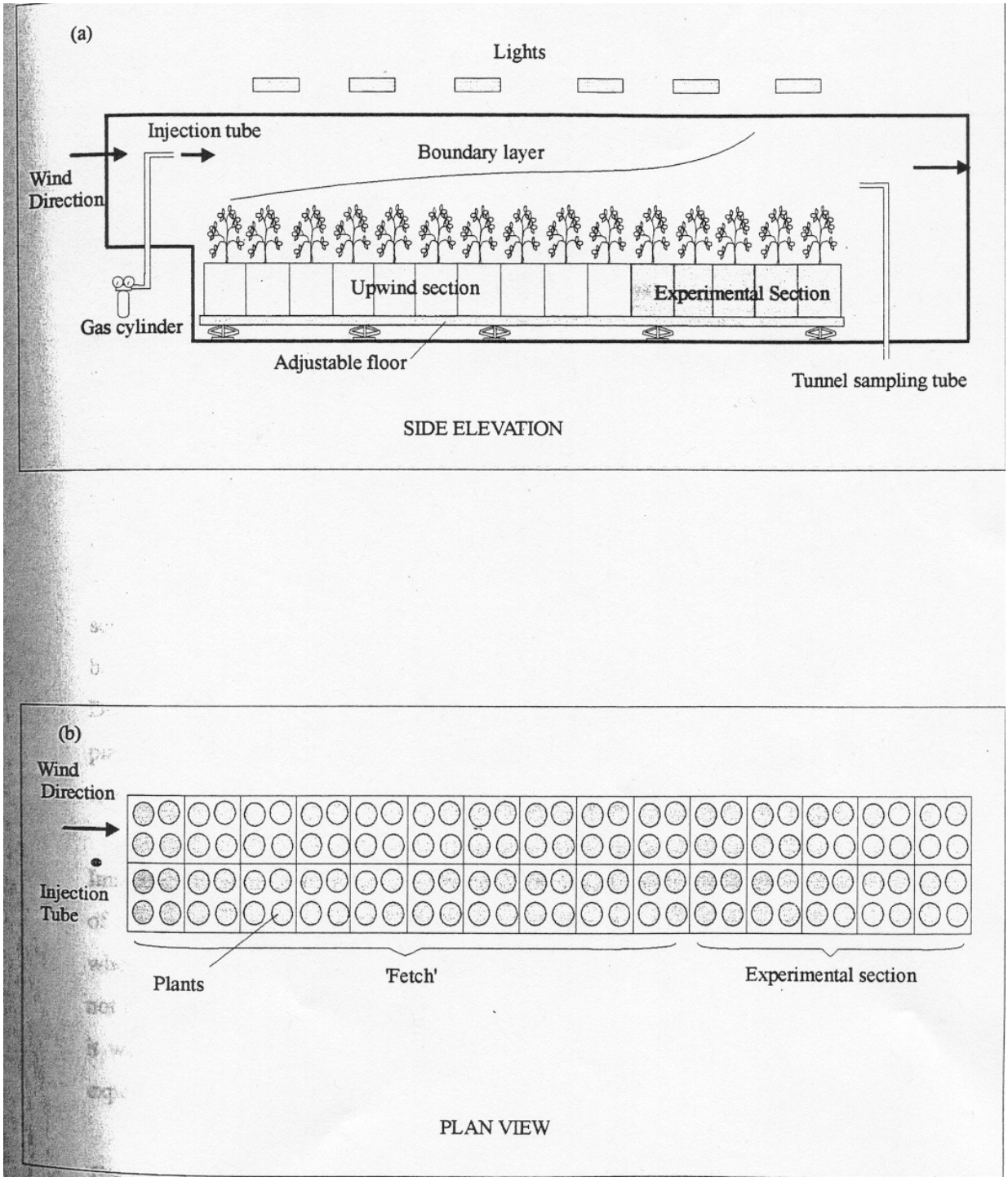

Figure A.1: Experimental canopy in wind tunnel side elevation (a) and plan view (b)

The air activity concentration for each exposure period was calculated as the total activity absorbed in the trapping solution divided by the total volume of air sampled. The air profiles presented in Figure A.2 are plots of average air activity concentration during the sampling period plotted at the mid point of the sampling period for each of the exposure experiments. These concentrations are given numerically in Table A.3, and C-14 integrated air concentrations are given in Table A.4. The ranges of temperature and photosynthetically active radiation (PAR) in the tunnel during each experiment are given in Table A.5. The canopy was illuminated with a bank of six 450 W agricultural lights set to a sixteen-hour photoperiod. The temperature in the tunnel increased with time during the fumigation (Table A.5) and the relative humidity increased by about 10%, with an average value of 55%. The average illumination was quite constant in

P2-P5, and decreased slightly with time for P1 and P6. The illumination was not uniform on all plants and the range in Table A.5 must be considered. The plants were under no water stress.

In experiment P1, 30 plants were used in the 10 sampling pots; 25 plants were used in P2 and 20 (2 per pot) in the rest of the fumigations.

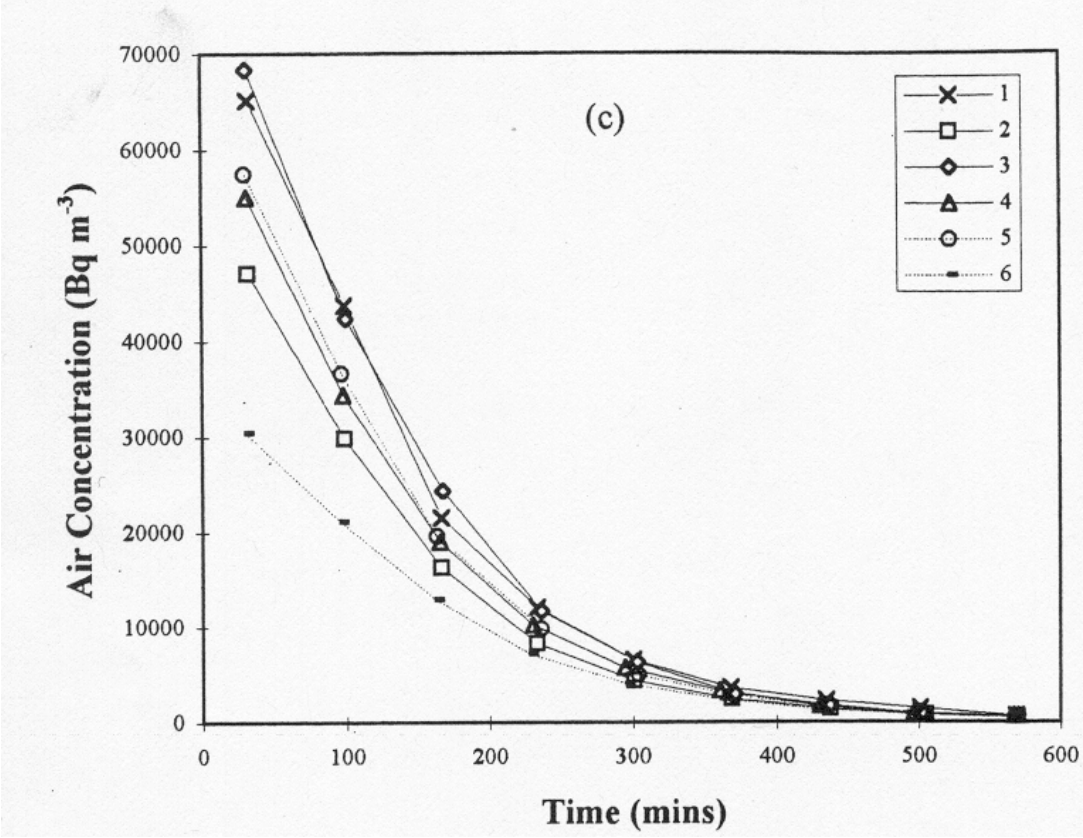

Figure A.2: C-14 activity concentrations in air in the wind tunnel during exposure

Table A.1: Fumigation schedule for experiments in which potato plants were exposed to $^{14}CO_2$

Code Nº of Experiment	Time of Fumigation (Days after sowing)	Fumigation date (d/m/y)
P1	21	25/8/95
P2	33	7/9/95
P3	47	21/9/95
P4	61	5/10/95
P5	74	18/10/95
P6	89	2/11/95

Table A.2: Potato sampling schedule

Harvest	Experiment											
	P1		P2		P3		P4		P5		P6	
	Age*	T**	Age	T	Age	T	Age	T	Age	T	Age	T
H1	21	0	33	0	47	0	61	0	74	0	89	0
H2	31	10	38	5	53	6	65	4	79	5	90	1
H3	38	17	44	11	58	11	72	11	83	9	93	4
H4	48	27	58	25	68	21	83	22	87	13	95	6
H5	72	51	79	46	83	36	90	29	93	19	97	8
H6	97	76	97	64	97	50	97	36	100	26	100	11

* days after sowing
** days after exposure

Table A.3: C-14 air concentration above the potatoes

P1		P2		P3		P4		P5		P6	
Time (min)	Air Conc (Bq/m3)	Time (min)	Air Conc (Bq/m3)	Time (min)	Air Conc (Bq/m3)	Time (min)	Air Conc (Bq/m3)	Time (min)	Air Conc (Bq/m3)	Time (min)	Air Conc (Bq/m3)
32	65121	32	47090	31	68339	31	55009	30	57453	30	30450
99	43715	99	29804	100	42376	98	34387	97	36612	96	21067
166	21521	166	16279	167	24373	165	18999	163	19576	162	12966
233	12095	233	8297	236	11749	230	10269	236	9906	228	7152
300	6577	301	4405	303	6361	294	5774	304	5028	295	4086
368	3667	369	2490	371	2983	360.5	3359	370	2858	361	2461
435	2325	438	1393	438	1827	430.5	1686	436	1646	426	1452
501	1460	505	801	504	839	496.5	985	501	954	492	900
569	701	570	565	570	694	567	651	568.5	607	566	507

Table A.4: C-14 integrated air concentration (IAC)

Experiment	IAC MBq m^{-3} min
P1	9.764
P2	6.983
P3	9.647
P4	8.089
P5	8.307
P6	4.774

Table A.5: Range of temperature (T) (^{o}C) and PAR (W/m^2) during fumigation

Experiment	Tmin	Tmax	PARmin	PARmax
P1	23	27	70	150
P2	21	26	50	160
P3	20	23	40	160
P4	19	24	30	130
P5	19	23	30	130
P6	17	20	30	130

Biomass dynamics

The average dry weight of the roots, leaves, stems and tubers, together with standard deviations (based on 2-6 plants), in all experiments for every harvest time are given in Table A.6 and Figure A.4. The development of leaf area index (LAI) is given in Figure A.3. The dry weight fractions for each harvest are given in Table A.7.

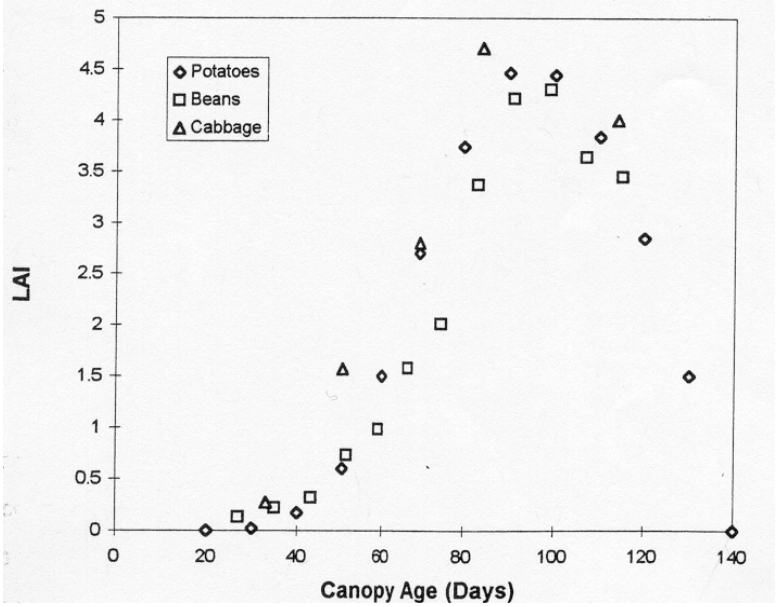

Figure A.3: Leaf area index development for potatoes, beans, cabbage

Table A.6: Biomass dynamics for potatoes

P1									
	Age	LEAVES	STDEV	STEMS	STDEV	ROOTS	STDEV	TUBERS	STDEV
H1	21	*3.2*	2.3	1.7	1	7.7	4.4	-	-
H2	31	10	8.4	7.5	7.1	1.3	1.1	-	-
H3	38	7	1.2	9.6	2.2	1.8	1.3	0.3	0
H4	48	15.5	9.4	15.5	8.6	2.7	1.4	11	8.3
H5	72	9.4	8.8	11.3	6	1.4	1.4	40.7	32.6
H6	97	6.8	8.3	14.7	6.1	1.3	1	78.3	87.2
P2									
	Age	LEAVES	STDEV	STEMS	STDEV	ROOTS	STDEV	TUBERS	STDEV
H1	33	11.2	5.1	11.9	4.7	2.9	1.5	-	-
H2	38	5.4	2.9	8	4.5	1.1	0.6	-	-
H3	44	6.5	4.6	10.9	5.6	1.9	1.1	3.8	0.7
H4	58	15.6	1.6	18.4	3	3.4	1.7	12.5	3
H5	79	15.4	15.7	14.7	8.8	1.3	1.2	45.3	47.5
H6	97	5	4.8	7.1	2.4	0.9	0.4	30.2	8.7
P3									
	Age	LEAVES	STDEV	STEMS	STDEV	ROOTS	STDEV	TUBERS	STDEV
H1	47	7.84	2.86	12.15	5.02	3.42	1.75	9.78	7.22
H2	53	12.77	4.9	11.98	5.08	2.76	1	13.29	11.2
H3	58	6.73	5.19	9.37	6.08	1.41	0.37	13.38	4.02
H4	68	6.33	5.38	11.95	9.77	1.59	0.91	16.34	12.73
H5	83	5.81	5.71	12.23	2.89	2.11	1.46	50.31	41.86
H6	97	2.74	1.75	8.66	0.54	0.7	0.08	46.46	19.1

P4									
	Age	LEAVES	STDEV	STEMS	STDEV	ROOTS	STDEV	TUBERS	STDEV
H1	61	15.53	7.05	22.62	9.39	2.71	1.55	27.59	27.76
H2	65	12.07	8.38	9.12	5.25	2.66	0.62	42.27	20.06
H3	72	4.42	2.42	7.93	4.1	1.02	0.76	24.53	12.11
H4	83	3.08	2.18	9.51	5.85	0.76	0.55	32.33	18.72
H5	90	7.72	8.1	16.29	19.02	1.45	0.35	35.67	10.73
H6	97	0.56	0.13	47.35	1.85	0.51	0.66	49.99	2.21
P5									
	Age	LEAVES	STDEV	STEMS	STDEV	ROOTS	STDEV	TUBERS	STDEV
H1	74	6	2.4	8.8	4.7	1.5	0.9	38.1	17.8
H2	79	4.2	2.2	8.2	2.6	0.7	0.3	24.3	18.9
H3	83	2.6	2.7	6.5	1.3	1.1	0.7	49.3	54.6
H4	87	4.3	2.4	8.2	2.1	1.6	0.6	75.8	25.8
H5	93	5.1	1.7	15.6	11.3	1.3	1	49.1	30.3
H6	100	2.2	1.9	14.7	2.6	1.6	0.8	76.9	6
P6									
	Age	LEAVES	STDEV	STEMS	STDEV	ROOTS	STDEV	TUBERS	STDEV
H1	89	6.21	6.76	14.03	14.9	0.99	0.36	36.66	14.17
H2	90	5.38	4.92	9.02	3.98	1.27	0.61	70.34	24.97
H3	93	6.9	4.96	17.02	7.57	0.69	0.44	48.18	9.43
H4	95	10.89	5.53	17.34	3.99	2.16	0.33	121.68	52.71
H5	97	7.52	8.28	17.08	10.93	1.18	1.47	77.58	68.4
H6	100	3.24	0.45	7.17	0.45	0.23	0.05	40.39	35.06

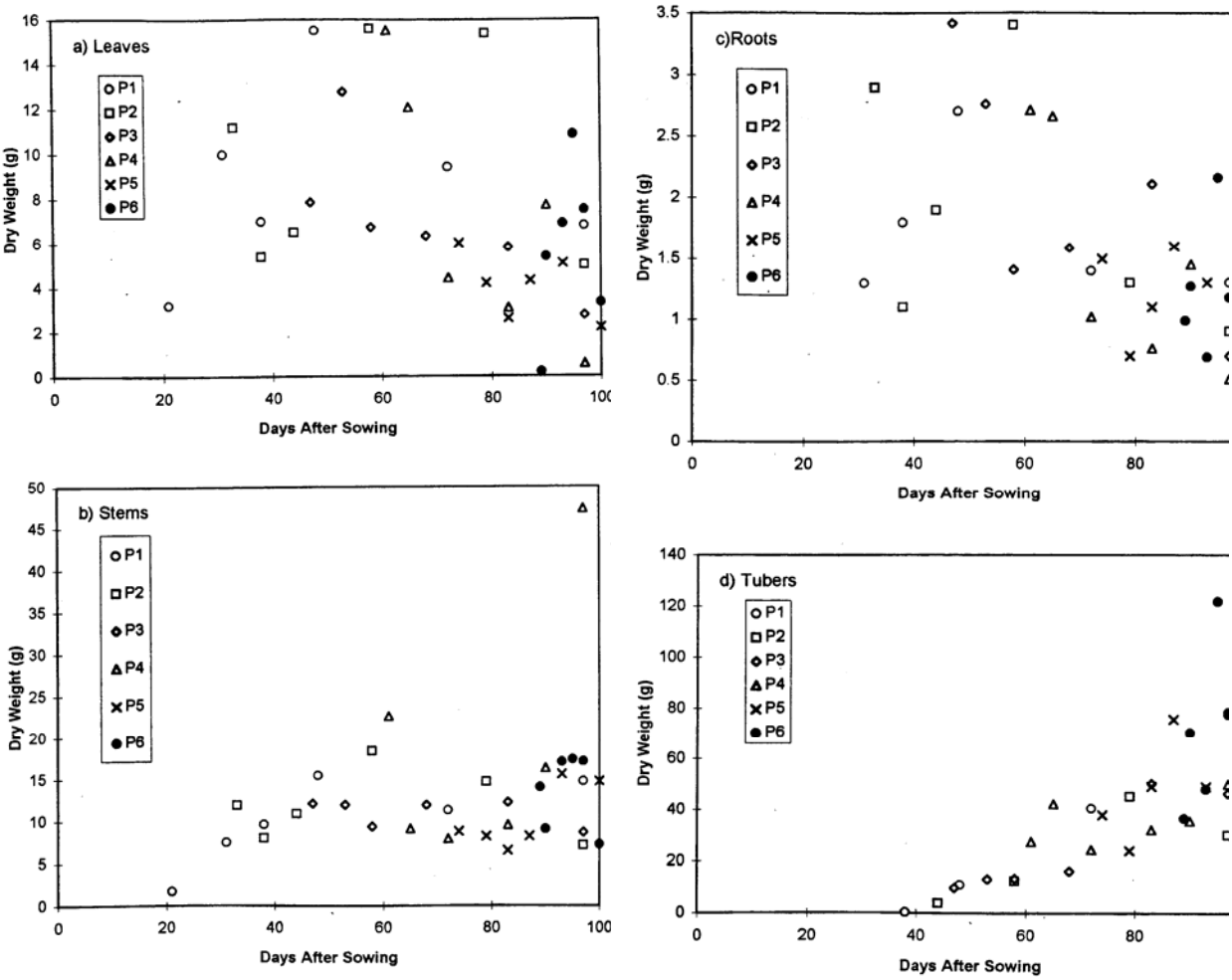

Figure A.4: Dry weights of potato leaves (a), stems (b), roots (c), tubers (d)

Table A.7: Dry weight fractions

P1	Dry weight fraction				
	Age	leaves	stems	roots	tubers
H1	21	0.06	0.02	0.07	-
H2	31	0.09	0.03	0.05	-
H3	38	0.06	0.04	0.07	0.12
H4	48	0.07	0.04	0.08	0.12
H5	72	0.08	0.04	0.07	0.16
H6	97	0.12	0.1	0.09	0.22
P2					
	Age	leaves	stems	roots	tubers
H1	33	0.08	0.04	0.08	-
H2	38	0.05	0.03	0.06	-
H3	44	0.06	0.04	0.06	0.31
H4	58	0.09	0.05	0.08	0.15
H5	79	0.09	0.05	0.06	0.18
H6	97	0.07	0.06	0.06	0.17
P3					
	Age	leaves	stems	roots	tubers
H1	47	0.06	0.05	0.08	0.13
H2	53	0.08	0.03	0.07	0.13
H3	58	0.09	0.04	0.05	0.13
H4	68	0.08	0.04	0.06	0.15
H5	83	0.09	0.05	0.06	0.17
H6	97	0.13	0.13	0.07	0.18
P4					
	Age	leaves	stems	roots	tubers
H1	61	0.08	0.04	0.07	0.15
H2	65	0.07	0.02	0.06	0.16
H3	72	0.09	0.05	0.07	0.18
H4	83	0.08	0.06	0.05	0.19
H5	90	0.17	0.07	0.06	0.16
H6	97	0.25	0.6	0.07	0.2
P5					
	Age	leaves	stems	roots	tubers
H1	74	0.08	0.04	0.05	0.18
H2	79	0.1	0.05	0.06	0.2
H3	83	0.14	0.04	0.07	0.18
H4	87	0.15	0.04	0.06	0.17
H5	93	0.16	0.08	0.08	0.19
H6	100	0.08	0.07	0.08	0.15
P6					
	Age	leaves	stems	roots	tubers
H1	89	0.14	0.06	0.07	0.17
H2	90	0.12	0.04	0.06	0.18
H3	93	0.41	0.07	0.06	0.19
H4	95	0.47	0.08	0.07	0.28
H5	97	0.6	0.13	0.09	0.21
H6	100	0.7	0.17	0.1	0.19

Calculation Endpoints:

Modelers are asked to calculate the following:

1) the carbon concentration in the leaves at each sampling time (H1 to H6) for each experiment (P1 to P6) [Bq/gdm];
2) the carbon concentration in the tubers at final harvest (H6) for each experiment [Bq/gdm];
3) 95% confidence intervals on all predictions.

The Modelers are also asked to supply a fully documented model description following the EMRAS template.

APPENDIX B

MODEL DESCRIPTIONS

Model description

The OURS0N model used by EDF is a dynamic model primarily developed to evaluate radionuclide concentrations in the aquatic and terrestrial environment resulting from liquid discharges. It assumes that the incorporation of C-14 in plants results from photosynthetic carbon assimilation, and that translocation occurs between the leaves, where photosynthesis takes place, and the storage organs. The net photosynthetic carbon assimilation rate, which is a function of leaf biomass, corresponds to the total growth rate of the plant. Allocation of photosynthates to different parts of the plant depends on the growth stage. For potatoes, two phases are considered: a vegetative stage where shoot growth occurs and a filling stage where tuber growth occurs.

Parameter Values

CO_2 air concentration during fumigation: 0.19 g C/m3
Daily net photosynthetic rate: 0.0495 g C/g leaf dry matter. (Variations due to solar radiation were not taken into account.)
Vegetative stage: from planting to 40 days of age
Filling stage: from 40 days of age until harvest
Translocation to tubers during vegetative stage: 0.10
Translocation to tubers during filling stage: 0.50
Fractional carbon content per unit dry biomass (dry) in leaf and tuber: 45%

Results

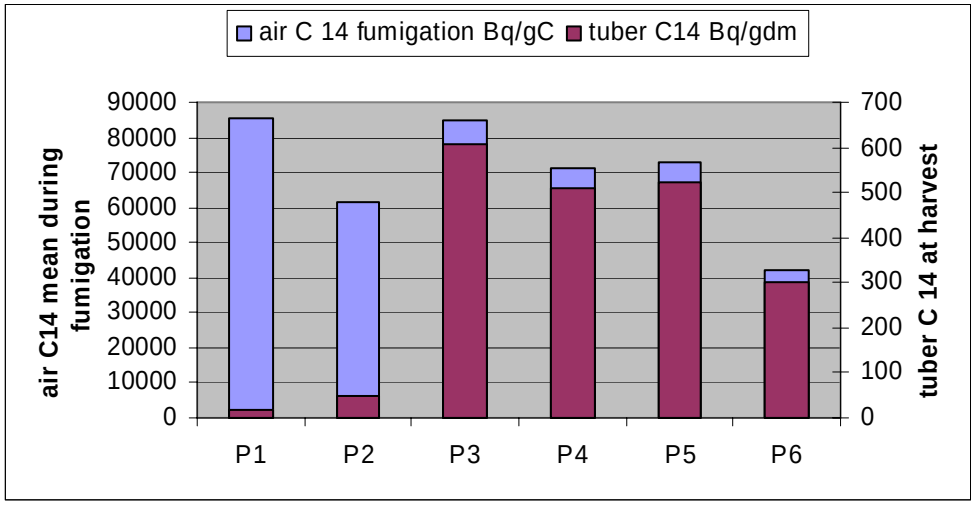

Figure 1. Observed C-14 concentrations in air during exposure and predicted concentrations in tubers at final harvest.

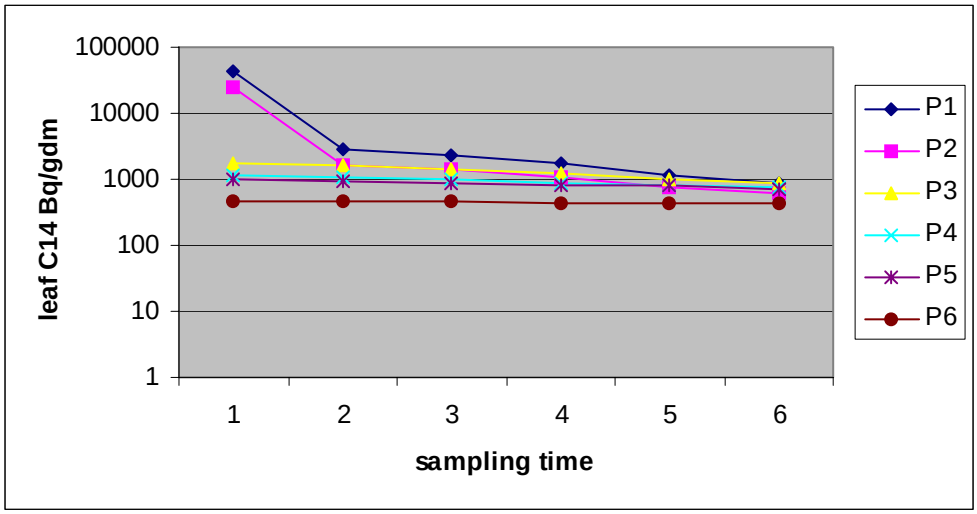

Table 2. Predicted C-14 concentrations in potato leaves at each sampling time for each experiment.

FSA Model

INTRODUCTION

Model Name: Prism 3.0, Special Radionuclides submodel: H-3 and C-14

Purpose of Model: Regulatory Assessment; Conservative

Type of Model: Dynamic; Numerical; Compartmental

Compartments Considered: Biological plant compartments include internal leaf, internal stem, internal grain/fruit, roots, plant water and energy storage. Environmental compartments include soil water, soil organic material and sink. The external parts of the plant are not explicitly represented because all sources are considered to be gaseous. The root store is not considered due to rapid redistribution of H-3 and C-14. Contamination in soil water and soil organic matter is distinguished

Transport Processes Considered: Uptake from air**;** sorption, advective transport and bioturbation in soil; plant uptake from soil and within plant transport via phloem and xylem.

Endpoints: C-14 concentration in each compartment at the end of the scenario.

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KEY ASSUMPTIONS

- Direct uptake from soil to internal plant: a single compartment is used for each soil layer. Sorption is assumed between C-14 in soil water and on soil particles.
- Plant water and stored energy are not represented. For C-14, soil mediated processes are considered less important compared with direct uptake from the atmosphere. The main carbon fluxes are governed by photosynthetic incorporation and respiratory loss.
- It is assumed that any carbon transfers from the plant or soil back to the atmosphere are rapidly lost from the system.
- “Labile” and “non-labile” pools are similar to those in the STAR model.

- The rate of carbon uptake during daylight hours is controlled by photosynthesis.
- Transfers between compartments are calculated using transfer rates or the fraction of activity transferred to each compartment

MATHEMATICAL FORMULATION

Plant concentrations C_p due to uptake by photosynthesis and by roots are given by

$$C_p = v_d^{co2} C A \quad (1)$$

where v_d^{co2} is the deposition velocity of CO_2;
A is the deposition rate taking place; and
C is the concentration of $^{14}CO_2$ in the atmosphere.

The deposition velocity is given by

$$v_d^{co2} = k G F_{GC} / C_C \quad (2)$$

where G is the biomass growth rate;
F_{GC} is the fraction of dry matter that is carbon; and
C_c is the concentration of carbon in the atmosphere.

The loss of activity by respiration from the energy store is given by

$$L = (k-1) G A F_{GC} / M_{ES} \quad (3)$$

where M_{ES} is the mass of carbon in the energy store.

The transfer rate from the energy store to the internal leaf is given by

$$T = G_{IL} A F_{GC} / M_{ES} \quad (4)$$

where G_{IL} is the growth rate of the internal leaf. Similar expressions are used to calculate transfers to root, stem and internal grain/fruit.

Equations (1) to (4) are solved using the AMBER Code.

TEMPORAL AND SPATIAL DISCRETIZATION OF THE MODEL

There is no spatial discretization in the model. The user can define the input air concentration as a continuous function, a spike (instantaneous exposure) or a series of spikes (complex exposure). Output is normally reported every three days unless specified otherwise. It is recommended to remove interim output times between the start and finish of the calculations and specify the times at which results are required. No spatial or temporal averaging was used for the potato scenario.

INPUT DATA REQUIRED

The model requires a number of soil and plant parameters. The growth curve may be adjusted to match information in the model scenario.

PARAMETER VALUES

Most input parameters were distributed and values in each run were determined by sampling in the assigned probability density function (PDF). The attributes of the PDFs for the key model parameters are listed in the following table.

Parameter	Units	Distribution Type	Range	Best Estimate
Soil surface bioturbation rate	d^{-1}	Lognormal	0.25 - 13	6
Organic degradation rate	d^{-1}	Triangular	5E-05 – 3E-02	4E-03
Adsorption rate	d^{-1}	Log uniform	3.5E-05 - 3.5E-03	3.5E-04
SA_foliage	d^{-1}	Log uniform	15 - 25	20
SA_grain	d-1	Log uniform	1 - 10	5
SA_stem	d-1	Log uniform	1 - 10	5
Fraction of CO_2 recycled during photosynthesis	Unitless	Lognormal	0.04 – 0.3	0.06
Biomass fraction in energy store	Unitless	Log uniform	0.001 – 0.02	0.002
Plant assimilation factor	Unitless	Uniform	0.4 – 0.6	0.5
Dry to fresh weight ratio	Unitless	Triangular	0.05 – 0.3	0.1

UNCERTAINTIES

Uncertainties were estimated using a probabilistic approach by sampling in the parameter PDFs. Some C-14 parameters were not sampled. If values are chosen at the 95% level, the predicted concentrations will be conservative by a factor of 7-10 (European Crop Protection Association Dietary Risk Assessment Workshop).

APPLICATION OF THE MODEL TO THE SCENARIO

- The exposure was assumed to be complex in form and modeled as a series of spikes, with different exposures for each experiment.
- The predicted plant biomass at the end of the calculations was scaled to the value observed in the experiments.
- The growth curve for the potatoes was adjusted so that enough growth occurred prior to exposure to ensure some uptake in the leaves for each experiment.

IFIN Models

1. Basic Modelling Principles

For this scenario, we used the WOFOST crop growth model, which was developed by the Wageningen School in The Netherlands. We ran WOFOST with both default potato parameters and parameters specific to a Scottish cultivar. We also used another model with simpler algorithms for dry matter production and initial inventory. The basic principles used in these models are as follows:

- The specific activity of C-14 transferred to the plant in a given time interval is the same as the average specific activity of the source over that interval.
- Under normal conditions, more than 90% of plant carbon comes from the atmosphere; this was assumed to be the case in the potato experiments.
- In biochemical reactions occurring in the plant, the discrimination factor between C-14 and C-12 is closed to 1 (0.96±0.02, Sheppard et al., 2005); consequently, modelling of C-14 transfer is the same as modelling stable carbon transfer.

The processes we considered in implementing the models were as follows:

- Initial incorporation of C-14 in the total plant;
- Loss of C-14 through maintenance and gross respiration;
- Distribution of dry matter to plant parts;
- Further growth dilution and potential translocation.

Each of these processes can be modelled simply or at a process level. We started with the process-oriented model WOFOST, drawing on our previous experience with the tritium module in RODOS (Real Time On-Line Decision Support System for Nuclear Emergencies). In addition, we used a simpler approach to modelling dry matter production.

2. WOFOST Model

2.1 Default Potato Parameters

Genotype has a large influence on plant growth. We first ran WOFOST using default parameter values that reflected a generic cultivar. Growth also depends on climate, but since weather data for 1995 were not available, we used historical data for Cambridge averaged over the 30-year period 1960-1990. This introduced an additional uncertainty into the calculations.

The photosynthesis submodel in WOFOST depends on photosynthetically-active radiation (PAR), leaf area index (LAI), and maximum leaf photosynthesis rate. An example is given in Figure 1. In the experiment, the potatoes were planted extremely late in the year, even for the UK. The normal planting time for England is late April or early May, but in the experiment it was August 4. In these circumstances, WOFOST with default parameter values slightly underestimated the observed biomass dynamics.

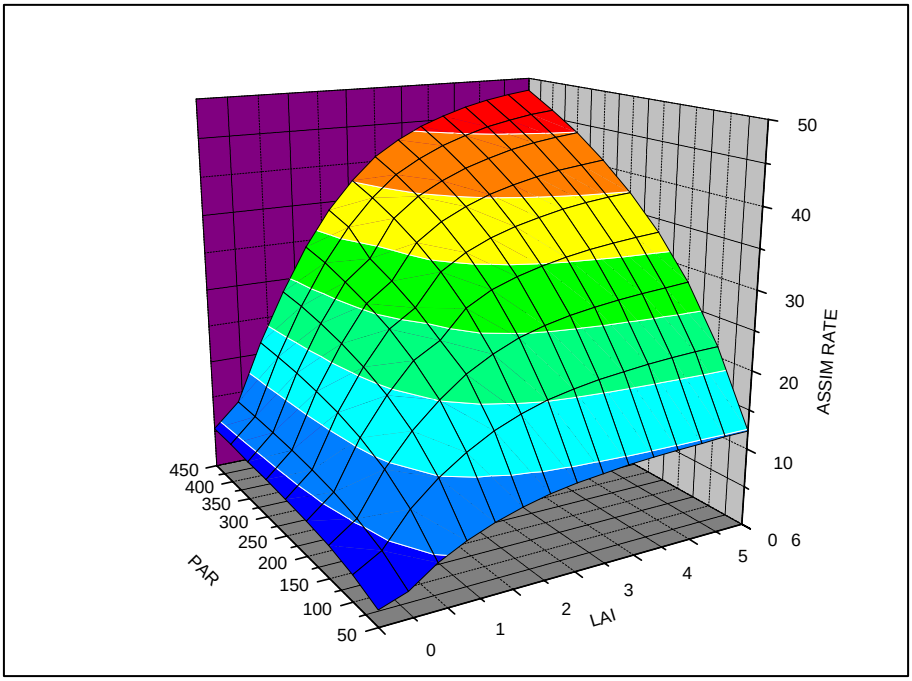

Figure 1. Dependence of photosynthesis rate on PAR and LAI for potatoes.

The gross canopy photosynthesis rate, A_{gross}, is parameterized in WOFOST as:

$$A_{gross} = A_{max}\ LAI^{1.33}/(K^{1.33} + LAI^{1.33}) \quad (1)$$

Here A_{max} is the asymptotic canopy photosynthetic rate, which depends on PAR in the following way:

$$A_{max} = a + b\ PAR - c\ PAR^2 \quad (2)$$

The parameter K is given by

$$K = d + e\ PAR \quad (3)$$

The parameters a, b, c, d and e have plant-specific values depending on canopy age and temperature.

2.2 WOFOST Default Predictions and Experimental Biomass Dynamics

WOFOST predictions of potato growth rates are compared with the experimental data in Figures 2 and 3. The model performs well for total above-ground biomass over the entire study period, and for tuber production at the start of the period. However, the growth rate for tubers is underestimated at later times.

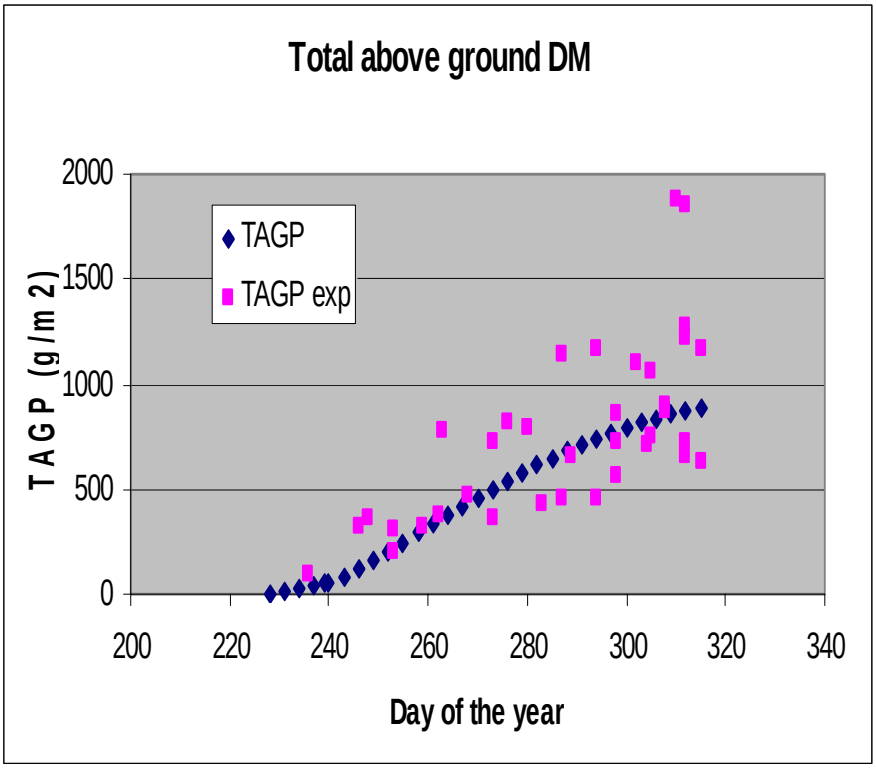

Figure 2. Comparison between WOFOST predictions and experimental data for total above ground biomass

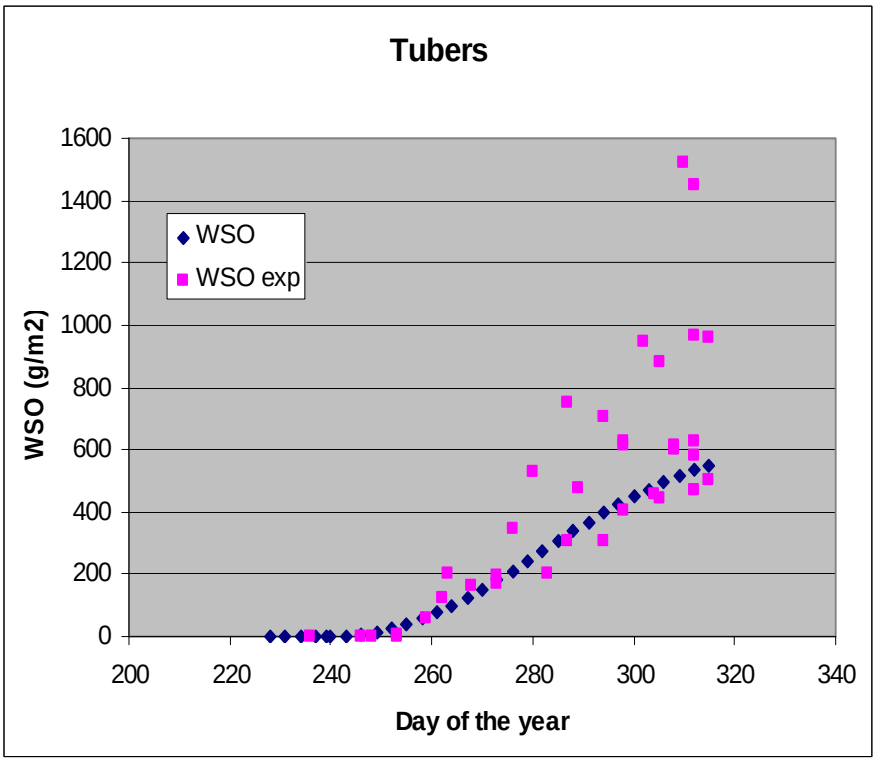

Figure 3. Comparison between WOFOST predictions and experimental data for tuber biomass

2.3 Initial C-14 Incorporation

The WOFOST model predicts the photosynthesis rate and C-14 incorporation into plants using the experimental data on PAR, LAI and temperature. Table 1 gives the initial rate of C-14 incorporation into the plants for each experiment.

Table 1. Initial C-14 incorporation per plant

Exp	Age (d)	Median Temp (C)	Median PAR (W/m^2)	LAI	A_{max}	A_{gross}		Rate of C-14 incorporation ($Bq/m^2/10h$)
						kg/ha/h	g/plant/10h	
P1	21	25	110	0.3	22.5	3	0.16	6.67
P2	33	23	105	0.5	26	5.5	0.35	12.22
P3	47	21	100	1	30	10.5	0.84	23.33
P4	61	22	80	2.5	30	14	1.12	31.11
P5	74	22	80	1.5	27	11	0.88	24.44
P6	89	18	80	1	15	6	0.48	13.33

The C-14 air concentration varied strongly during the exposures, decreasing by a few orders of magnitude in the 10 hours of the experiment. Once the exposure was over and there was no further transfer of C-14 from air to plant, the plant C-14 concentration decreased due to respiration. Maintenance and growth respiration are not instantaneous processes. They have fast and slow components with rates of about 2 and 0.2 d^{-1}, respectively. WOFOST includes a fully dynamic treatment of incorporation and respiration, which mathematically is represented by an integral convolution. At harvest H1, respiration is not finished. At harvest H2, respiration is finished and we can apply simpler relationships for dry matter production.

2.4 Dynamics of Incorporation and Respiration

At harvest H1, we can approximate the dynamics with a constant air concentration and an average between gross photosynthesis and final dry matter production (Figure 4).

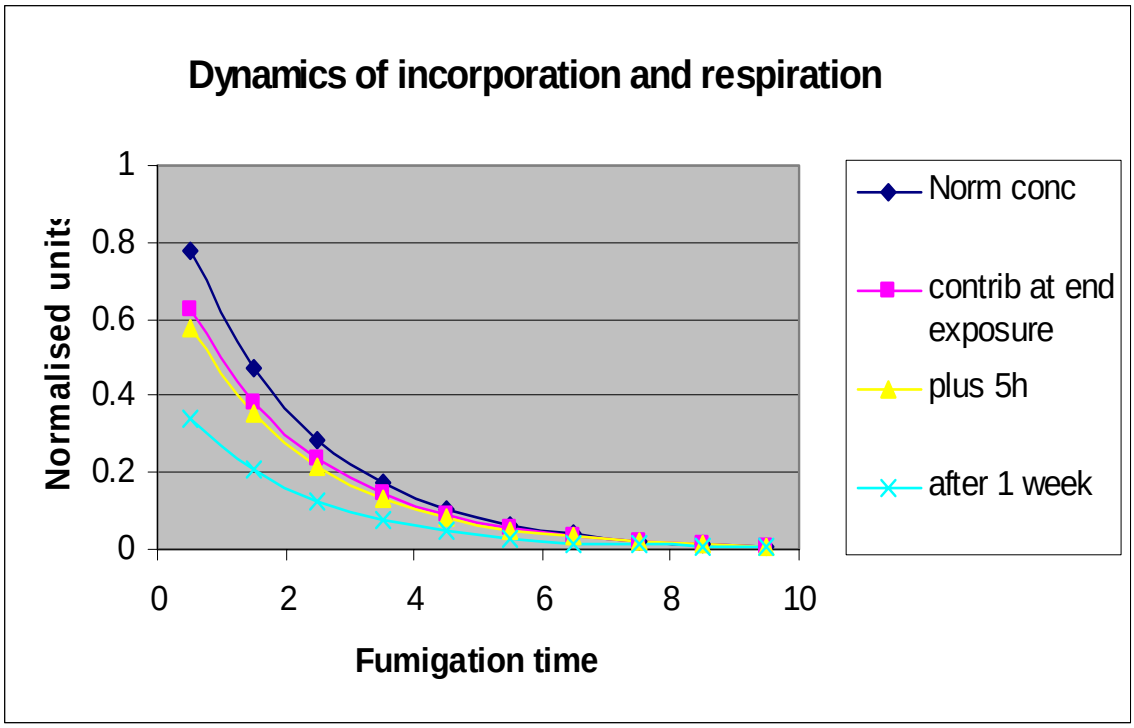

Figure 4. The dynamics of C-14 incorporation and respiration

Figure 5 shows the predicted to observed (P/O) ratio for the C-14 concentration in the total plant at harvest H1. The model performs well for plants exposed early in their growth cycle, but overestimates the concentration for plants exposed at later times.

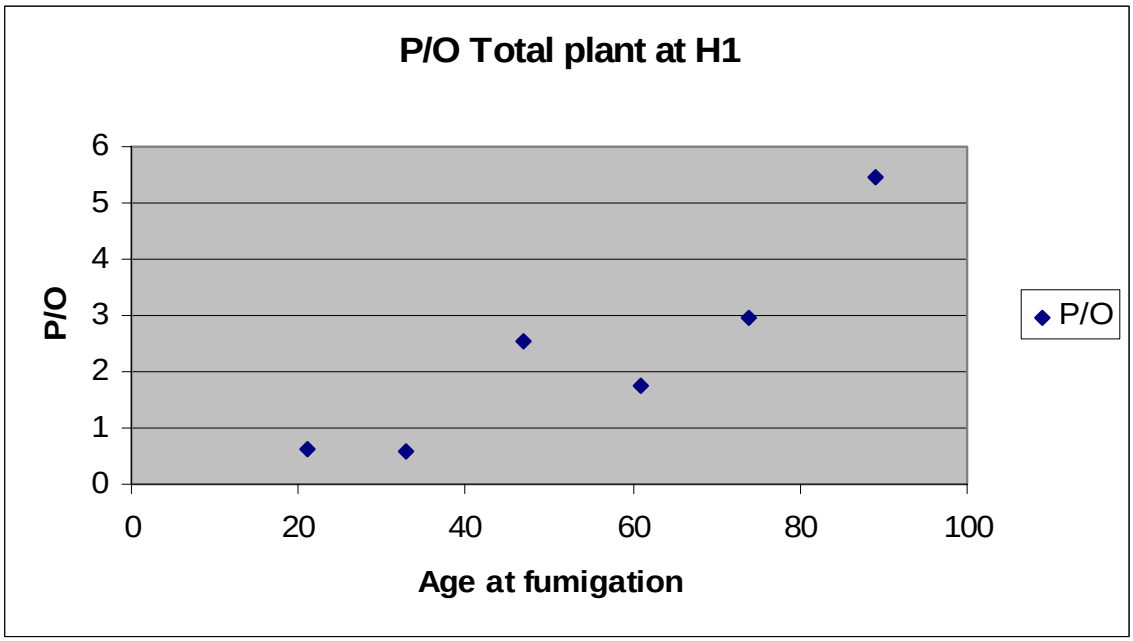

Figure 5. Predicted to observed ratio of C-14 concentration in the total plant at harvest H1.

Experimental and model uncertainties are not shown in the above figure. Experimental uncertainty is at least a factor 2, and model uncertainty is larger still.

2.5 Distribution of New Dry Matter to Plant Parts

Partition fractions (the fractions of newly-incorporated dry matter that appear in different parts of the plant) depend on the development stage of the plant and the crop genotype. The development stage (DVS) is defined to lie between 0 and 2, with a value of 1 marking the transition from vegetative stage to reproductive stage (the start of tuber formation). There are potato cultivars with early or late tuber formation and this influences the partition fractions to all plant parts. Both default WOFOST partition fractions (Table 2) and data for a Scottish potato genotype (Kooman and Spitters, 1995; Table 3) were used to test the importance of the partition processes on the model results. The predictions for C-14 concentrations in tubers at harvest were better for the Scottish genotype.

Table 2. Default WOFOST partition fractions

Exp	Age (d)	DVS	Root fraction	Leaf fraction	Stem fraction	Tuber fraction
P1	21	0.55	0.2	0.64	0.16	0
P2	33	0.87	0.2	0.64	0.16	0
P3	47	1.15	0.1	0.36	0.198	0.342
P4	61	1.37	0	0	0	1
P5	74	1.58	0	0	0	1
P6	89	1.82	0	0	0	1

Table 3. Partition fractions for Scottish cultivar

Exp	Age (d)	DVS	Root fraction	Leaf fraction	Stem fraction	Tuber fraction
P1	21	0.55	0.2	0.4	0.4	0
P2	33	0.87	0.2	0.24	0.48	0.08
P3	47	1.15	0.1	0.18	0.36	0.36
P4	61	1.37	0	0.05	0.09	0.86
P5	74	1.58	0	0.03	0.05	0.92
P6	89	1.82	0	0.017	0.017	0.966

3. Simple Model

The simple model considers dry matter production only, predicting the dry mass increment ΔW from the following equation (Kooman and Spitters, 1995):

$$\Delta W = \text{LUE Flint PAR}$$

where LUE is light use efficiency (g/MJ), an empirical parameter; and
Flint is light interception, which depends on leaf area index (LAI) and the extinction coefficient for photosynthetically-active radiation.

The predictions of the simple model are similar to those of WOFOST (Figure 6). The simple model can be used together with partition fractions and growth dilution to predict C-14 concentrations in the plant. However, only the WOFOST approach can explain sources of uncertainty in the predictions.

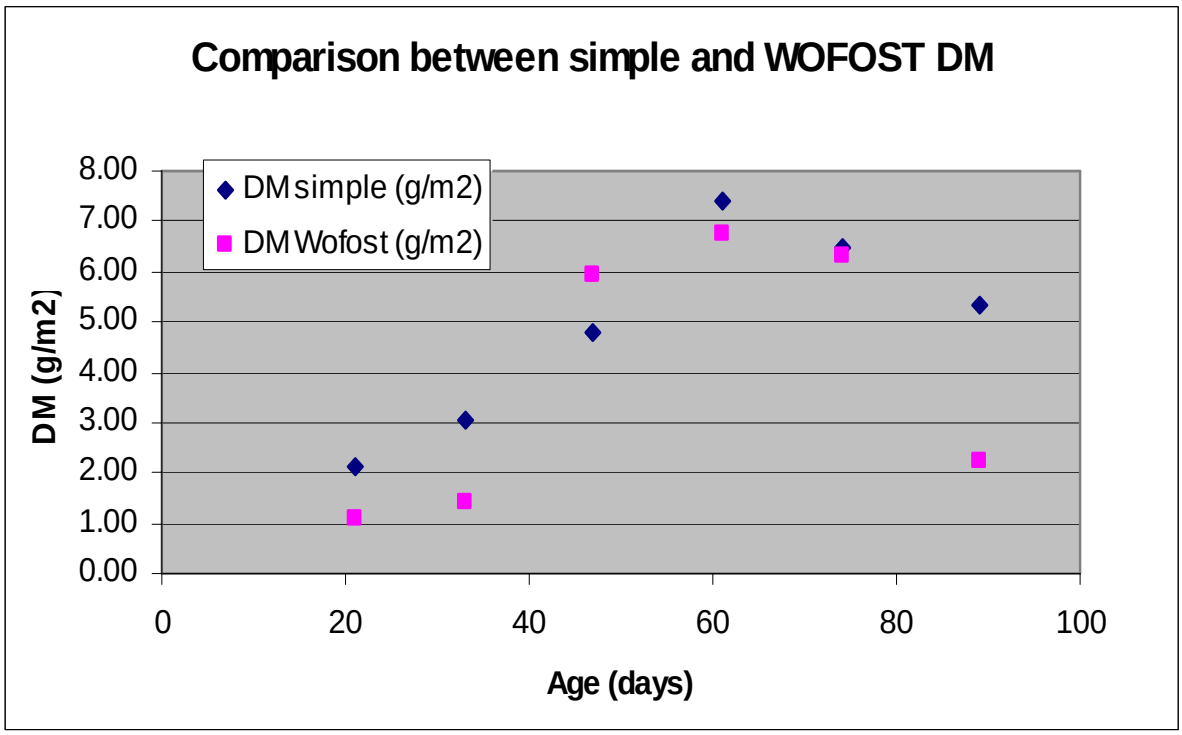

Figure 6. Comparison between the predictions of WOFOST and the simple model for dry matter (DM) production

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UTTY Model

1. Model Features

Our model, a dynamic compartment model shown in Figure 1, was developed using the MOGRA tool (Migration Of GRound Additions). The model consists of five compartments:

- Two organic compartments (stem-leaf-root and tuber)
- One inorganic compartment (whole plant)
- Two environmental compartments (air and soil)

Our potato model is almost the same as the rice model used in the EMRAS rice scenario. The [ear_org] compartment in the rice model is substituted by the [tuber_org] compartment in the potato model. Differences between the growth rates of potatoes and rice are also considered.

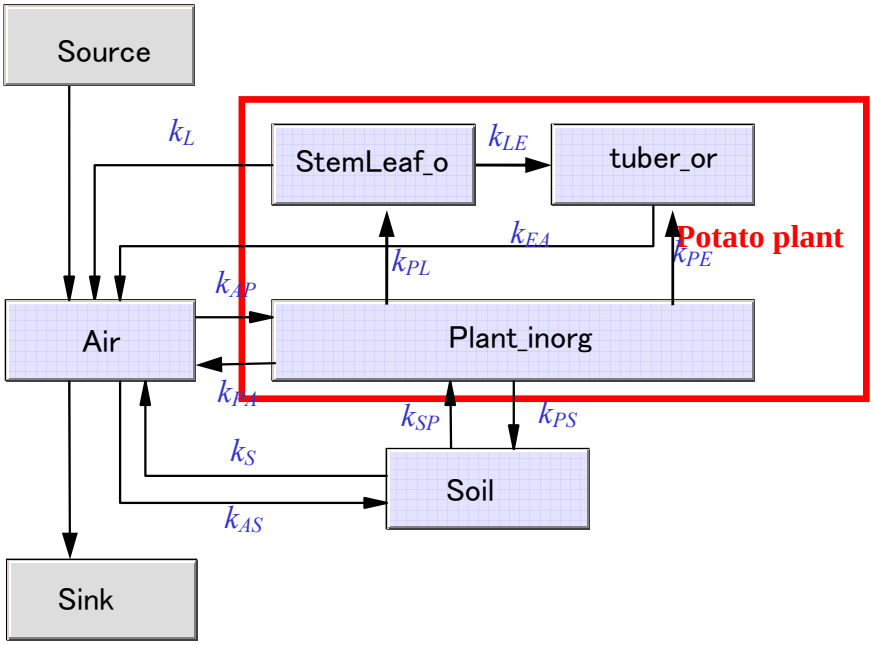

Figure 1. Potato model of UTTY

2. Compartments and Transfer Pathways

The compartments and transfer pathways considered in the UTTY model are shown in Figure 2. The [Plant_inorg] compartment includes the following;

a) non-fixed (inorganic) carbon in the plant
b) organic carbon that is readily exchangeable with air

This compartment considers photosynthesis in the leaves, but the photosynthates generated are not fixed here but rather in the [StemLeaf_org] and [Tube_org] compartments through the transfer parameters K_{PL} and K_{PE}. The [StemLeaf_org] compartment includes the photosynthates fixed in the stem, leaf and root. The amount of photosynthate in this compartment decreases

over time because of dark respiration and because most of the photosynthates are directed to the tubers after flowering.

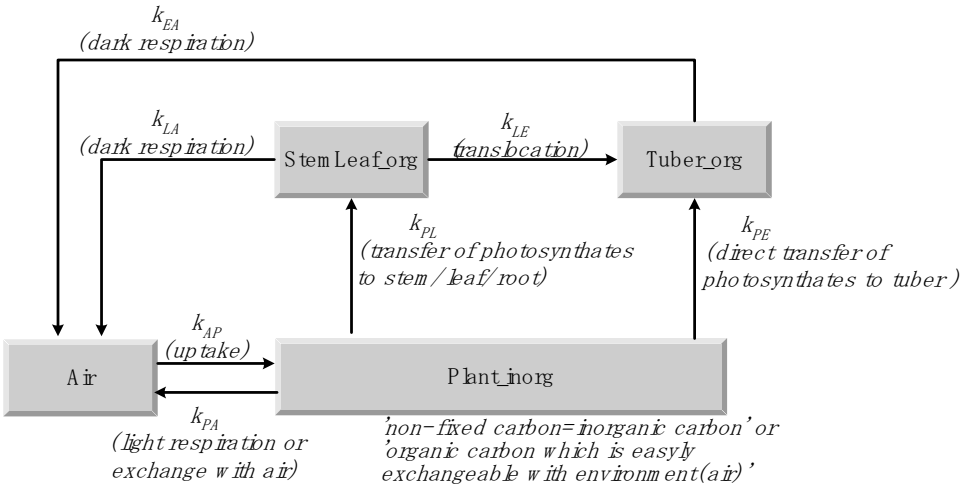

Figure 2. Compartments and transfer paths in the UTTY potato model.

The [Tuber_org] compartment includes the photosynthates transferred from [Plant_inorg] and/or from [StemLeaf_org] and fixed in the tuber. The amount of photsynthate in this compartment decreases due to dark respiration only.

The [K_{PA}] transfer path represents transfer of carbon from [Plant_inorg] to [Air] due to daylight respiration and/or exchange. The [K_{PE}] transfer path describes the transfer of photosynthates from [Plant_inorg] to [Tuber_inorg] after flowering. Similarly, the [K_{LE}] pathway represents the transfer of photosynthates from [Stemleaf_org] to [Tuber_org] after flowering. Photosynthates are transferred preferentially to the tuber at this stage of plant growth.

The ratio of K_{PE} to (K_{PE} + K_{LE}) depends on the growth rate of the tuber.

3. Transfer Factor Equations

i) Air compartment to Plant_inorg compartment: [K_{AP}] is given by the following equation, which is derived in more detail in the Annex:

$$k_{AP} = R_{air} \cdot \left[\alpha_{ino} \cdot \frac{dW_P}{dt} + \left(1 + \beta_{P\_res}\right) \cdot \alpha_{org} \cdot \frac{d}{dt}\left(W_P - W_E\right) + \left(1 + \beta_{E\_res}\right) \cdot \alpha_{E\_org} \cdot \frac{dW_E}{dt} \right] \Big/ W_A \quad \text{---------- (1)}$$

where R_{air} = ratio of carbon intake from air to total intake from air and soil (= 0.999)
α_{ino} = ratio of weight of inorganic carbon to total plant weight (= 0.02)
α_{org} = ratio of weight of organic carbon to the weight of the whole plant without the tuber (α_{org} = 0.37) or to the weight of the tuber (α_{E_org} = 0.40)
β_{res} = ratio of organic carbon used in respiration to the whole plant without the tuber (β_{P_res} = 0.35) or to the tuber alone (β_{E_res} = 0.15)
W_P, W_E = total plant and tuber weights (g), which are functions of their respective growth curves
W_A = weight of carbon in air (g/m^3)

The reverse transfer ([Plant_inorg] to [Air]), which represents daylight respiration, is not considered, so that

$$K_{PA} = 0 \quad \text{----------} \quad (2)$$

ii) Soil compartment to Plant_inorg compartment: It is assumed that the concentration in soil quickly equilibrates with the concentration in air. K_{SA} and K_{AS} are set to achieve this assumption. Thus the equations for K_{SP} and K_{PS} are identical to those for K_{AP} and K_{PA} respectively, but with W_A replaced by W_S (weight of carbon in soil) and R_{air} replaced with (1-R_{air}).

iii) Plant_inorg compartment to StemLeaf_org compartment: K_{PL} is given by

$$k_{PL} = \left[\left(1 + \beta_{P\_res}\right) \cdot \alpha_{org} \cdot \frac{d}{dt}\left(W_P - W_E\right) + \left(1 + (1-\gamma)\beta_{E\_res}\right) \cdot \alpha_{E\_org} \cdot \frac{dW_E}{dt} \right] \Big/ \left(W_P \cdot \alpha_{ino}\right) \quad \text{----------} \quad (3)$$

where γ is the ratio of transfer from [StemLeaf_org] to [tuber_org] to the total transfer from all pathways to [tuber_org].

iv) Plant_inorg compartment to tuber_org compartment: K_{PE} is given by

$$k_{PE} = \gamma \cdot \alpha_{E\_org} \cdot \left(1 + \beta_{E\_res}\right) \cdot \frac{dW_E}{dt} \Big/ \left(W_P \cdot \alpha_{ino}\right) \quad \text{----------} \quad (4)$$

v) StemLeaf_org compartment to tuber_org compartment: K_{LE} is given by

$$k_{LE} = \left(1 - \gamma\right) \cdot \alpha_{E\_org} \cdot \left(1 + \beta_{E\_res}\right) \cdot \frac{dW_E}{dt} \Big/ \left\{\left(W_P - W_E\right) \cdot \alpha_{org}\right\} \quad \text{----------} \quad (5)$$

In the UTTY model, the transfer of photosynthetic products to the tuber is assumed to occur from both [Plant_inorg] and [StemLeaf_org]. After flowering, the photosynthetic products are directly transferred to the tuber rather than to the stem and the leaves. We recently included the direct path from [Plant_inorg] to [tuber_org] in the model. The relative contributions of the two pathways are determined by the γ factor (Equation 3), which depends on the stage of tuber growth. The following functional relationship was obtained by analysis of the growth curve for rice:

$$\gamma = 1 - \frac{dW(t)}{dW_{\max}} \times 0.7 \quad \text{----------} \quad (5\text{-}1)$$

where

$$dW_{\max} = \frac{dW(t = t_{half\_tuber})}{dt} \quad \text{----------} \quad (5\text{-}2)$$

and $dW(t)$ = differential increase in tuber weight (g)
dW_{max} = maximum differential increase in tuber weight (g)
t_{half_tuberr} = day at which tuber weight becomes half its maximum value

vi) StemLeaf_org compartment to Air: This pathway represents dark respiration by the stem and leaves. K_{LA} is given by

$$k_{LA} = \beta_{P\_res} \cdot \alpha_{org} \cdot \frac{d}{dt}(W_P - W_E) \Big/ \{(W_P - W_E) \cdot \alpha_{org}\} \quad \text{----------} \quad (6)$$

vii) Tuber_org compartment to Air: K_{EA} describes dark respiration by the tuber and is given by

$$k_{EA} = \beta_{E\_res} \cdot \alpha_{E\_org} \cdot \frac{dW_E}{dt} \Big/ \{\alpha_{E\_org} \cdot W_E\} \quad \text{----------} \quad (7)$$

4. Growth Curves

The growth curves for the total plant and for the tuber were both assumed to be sigmoidal (Figure 3):

$$W(t) = W_{harvest} \cdot \frac{10^{K(t-t_{half})}}{1+10^{K(t-t_{half})}} \quad \text{----------} \quad (8)$$

where $W(t)$ = total weight of plant (or tuber weight) at time t (g)
$W_{harvest}$ = total weight of plant (or tuber weight) at harvest (g)
K = shape parameter of the sigmoid curve (d^{-1})
t = time (d)
t_{half} = day at which the whole plant weight becomes half its maximum value

The factors K and t_{half} were assigned different values for total plant and tuber.

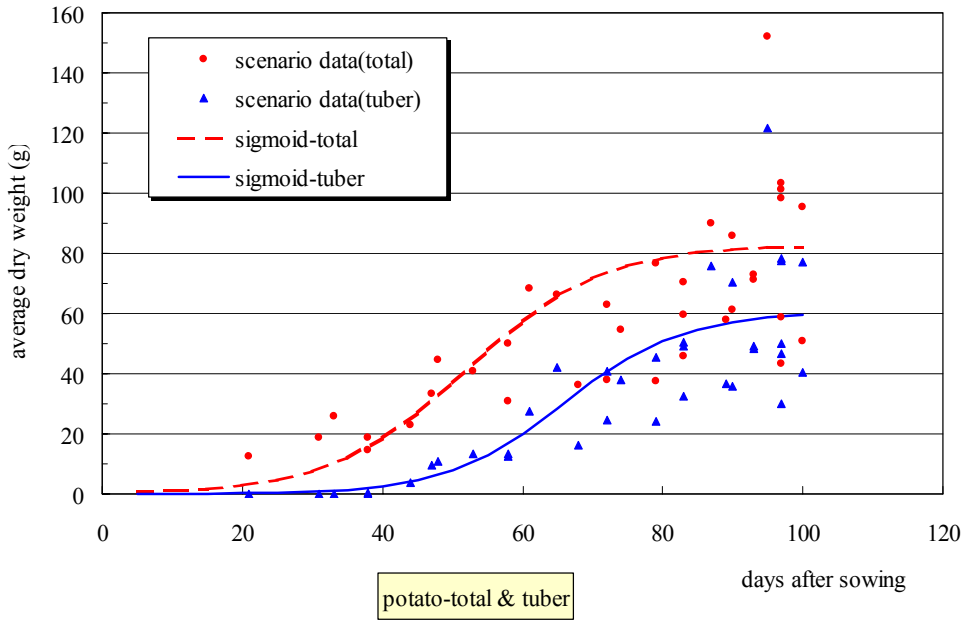

Figure 3. Observed time-dependent dry weights of the total potato plant and the tuber in the scenario and their sigmoid curves

The parameters in Eq.(8) were given the values shown in Table 1, based on the experimental data in the scenario description. It was assumed that the plants were sown on day 0, that the tubers started to grow on day 40 and that the plants were harvested on day 100.

Table 1. Values of the parameters in the sigmoidal growth curves.

Plant part	Final dry weight (g) ($W_{harvest}$)	t_{half} (d)	Shape parameter (d^{-1}) (K)
Whole plant	83	52	0.04
Tuber	61	66	0.052

Time-dependent whole plant weights calculated from the sigmoid curves of plant growth are shown in Table 2 for each experiment.

Table 2. Time-dependent weights of the whole plant calculated from the sigmoid curves of plant growth for each experiment.

	P1		P2		P3		P4		P5		P6	
	Day	Weight	Day	Weight	Day	Weight	Day	Weight	Day	Weight	Day	Weight
H1	21	2.93	33	9.01	47	25.30	61	38.03	74	31.51	89	24.31
H2	31	7.54	38	13.69	53	33.05	65	37.36	79	28.21	90	24.09
H3	38	13.69	44	21.13	58	37.15	72	32.98	83	26.22	93	23.57
H4	48	26.69	58	37.15	68	35.79	83	26.22	87	24.82	95	23.31
H5	72	32.98	79	28.21	83	26.22	90	24.09	93	23.57	97	23.11
H6	97	23.11	97	23.11	97	23.11	97	23.11	100	22.89	100	22.89

5. Air Concentrations

The UTTY model assumes that the air concentration during exposure is constant over time. A mean concentration for input to the model was obtained by dividing the integrated air concentration by the exposure time (600 min) to give the values in the third column of Table 3 (the [A] concentrations). However, the C-14 amounts in the Plant_inorg compartment show the effects of the long tail of the exposure (Figure 4). This implies that each part of the potato plant (stem, leaf and tuber) was exposed for more than 10 h. The C-14 amount in the Plant_inorg compartment should quickly become zero (equal to the C-14 concentration in air) after the 10-h exposure; the model should be improved in the future to ensure this. But for the present calculations, the air concentration was adjusted so that the time-integrated C-14 amount in the Plant_inorg compartment became equal to the amount that would have been seen in that compartment during a 10-h exposure to the [A] air concentrations (Figure 4). This resulted in the [B] air concentrations (the last column in Table 3), which were used in the analysis. The ratio of the C-14 amount during the 10-h exposure to the time integrated C-14 amount in the Plant_inorg compartment is different for each experiment because the plant growth rate is different.

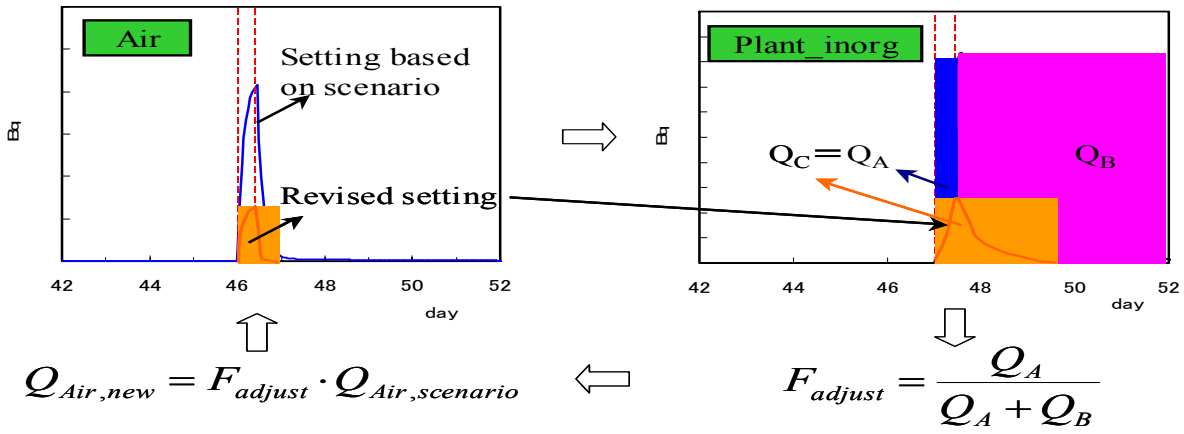

Figure 4. Adjustment of the amount of carbon in the air compartment.

Table 3. Air concentrations used in the calculations

Experiment	Integrated air concentration (Bq min/m^3)	Air concentration [A] (Bq/m^3)	Air concentration [B] (Bq/m^3)
P1	9.76×10^6	1.63×10^4	3070
P2	6.98×10^6	1.16×10^4	1877
P3	9.65×10^6	1.61×10^4	1870
P4	8.09×10^6	1.35×10^4	870
P5	8.31×10^6	1.39×10^4	610
P6	4.77×10^6	7.96×10^3	1372
Remark	Table 4 in the scenario description	Column 2 divided by 600	Column 3 adjusted (see text and Fig. 4)

Annex

Derivation of Equation (1) for K_{AP} (transfer from Air to the Plant_inorg compartment)

K_{AP} (Equation 1) is determined by all of the increases and decreases of carbon in the plant:

K_{AP} = [increase of inorganic carbon resulting from plant growth]
+ [increase of carbon by photosynthesis]
+ [decrease of carbon by light respiration]
+ [decrease of carbon by dark respiration of stem and leaves]
+ [decrease of carbon by dark respiration of tuber]

$$= k_{AP\_ino} + k_{AP\_org} + k_{AP\_res} + k_{AP\_P\_res} + k_{AP\_E\_res}$$

where

$$k_{AP\_ino} = R_{air} \cdot \alpha_{ino} \cdot \frac{dW_P}{dt} \Big/ W_A \quad \text{----------} \quad \text{(A-1)}$$

$$k_{AP\_org} = R_{air} \cdot \frac{d}{dt}\left\{\left(W_P - W_E\right) \cdot \alpha_{org} + W_E \cdot \alpha_{E\_org}\right\} \Big/ W_A \quad \text{----------} \quad \text{(A-2)}$$

$$k_{AP\_res} = R_{air} \cdot \beta_{Pl\_res} \cdot \alpha_{ino} \cdot \frac{dW_P}{dt} \Big/ W_A \quad \text{----------} \quad \text{(A-3)}$$

$$k_{AP\_P\_res} = R_{air} \cdot \beta_{P\_res} \cdot \alpha_{org} \cdot \frac{d\left(W_P - W_E\right)}{dt} \Big/ W_A \quad \text{----------} \quad \text{(A-4)}$$

$$k_{AP\_E\_res} = R_{air} \cdot \beta_{E\_res} \cdot \alpha_{E\_org} \cdot \frac{dW_E}{dt} \Big/ W_A \quad \text{----------} \quad \text{(A-5)}$$

Since daylight respiration is not considered in the model,

$$k_{AP\_res} = 0 \quad \text{----------} \quad \text{(A-6)}$$

K_{AP} is given by the sum of Equations (A-1) to (A-6):

$$k_{AP} = R_{air} \cdot \left[\alpha_{ino} \cdot \frac{dW_P}{dt} + \left(1 + \beta_{P\_res}\right) \cdot \alpha_{org} \cdot \frac{d}{dt}\left(W_P - W_E\right) + \left(1 + \beta_{E\_res}\right) \cdot \alpha_{E\_org} \cdot \frac{dW_E}{dt}\right] \Big/ W_A$$

---------- (A-7)

K_{PL} (Equation 3) and K_{EA} (Equation 7) are obtained in the same manner.