CONTRIBUTION OF ^{137}Cs TO THE TOTAL ABSORBED GAMMA DOSE RATE IN AIR IN A GREEK FOREST ECOSYSTEM: MEASUREMENTS AND MONTE CARLO COMPUTATIONS

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Abstract—**The absorbed gamma dose rate in air 1 m above soil due to natural gamma emitters and ^{137}Cs from the Chernobyl accident was determined inside a Quercus conferta Kit ecosystem in Northern Greece by combination of Monte Carlo simulations with the MCNP code and *in-situ* gamma spectrometry measurements. The total absorbed gamma dose rate in air is about 64 nGy h^{-1}, where 40% of this value is due to ^{137}Cs and 60% to natural gamma emitters. The Monte Carlo simulations indicated that the gamma absorbed dose rate in air due to ^{137}Cs is mainly due (70%) to unscattered radiation and to a lesser extent (30%) to the scattered radiation. The results obtained with the Monte Carlo simulations for the unscattered radiation were in very good agreement with the experimental values deduced by *in-situ* gamma spectrometry measurements. From the combination of the Monte Carlo simulations and *in-situ* gamma spectrometry measurements a conversion factor $C = 1$ nGy h^{-1}/kBq m^{-2} was deduced for ^{137}Cs. This factor must be used with caution and only for forest sites similar to the one used for this work.**

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Key words: ^{137}Cs; Monte Carlo; gamma radiation; Chernobyl

INTRODUCTION

Following the Chernobyl accident a number of semi-natural environments were contaminated by radiocesium mainly through wet deposition. These semi-natural ecosystems include among others upland pastures, moorland dominated by heather, alpine meadows, and coniferous and deciduous forests. Radiocesium deposited in these areas has a long-term impact on the environment, such as the increase of the external gamma dose rate. This fact is attributable to the persistence of radiocesium in all compartments of forests, pastures, and natural meadows. During the last 10 y, a scientific effort is evident towards the comprehension of the mechanisms that govern the transfer phenomena of radionuclides in the semi-natural ecosystems (Desmet and Myttenaere 1988; Bunzl and Kracke 1988; Heinrich et al. 1989; Wirth et al. 1997; Bunzl et al. 1989; Miller et al. 1990; Nimis et al. 1994; Ronneau et al. 1991; Belli et al. 1994). Specialized international conferences (Desmet et al. 1990) as well as international research projects coordinated by IAEA and CEC were dedicated to this subject.

In the framework of such a CEC-coordinated project (Wirth et al. 1997), we had studied systematically (Antonopoulos-Domis et al. 1997) over the last years the radiocesium dynamics in a Quercus conferta Kit ecosystem at Taxiarchis forest at Chalkidiki, 50 km from Thessaloniki in Northern Greece, which is a characteristic of broad leave forest ecosystems in Greece. The radiocesium distribution in the different parts of the ecosystem (soil, forest floor, ground vegetation, trunk, bark, branches, leaves) has been extensively measured. In the present work we studied the contribution of radiocesium to the total external gamma dose rate in air inside the forest by a combination of *in-situ* gamma spectrometry measurements and Monte Carlo simulations. The results obtained from this study are discussed here.

MATERIALS AND METHODS

The contribution of radiocesium to the total external gamma dose rate in air inside the forest is deduced by a combination of *in-situ* gamma spectroscopy and Monte Carlo simulations. The portable Ge detector used for the *in-situ* measurements is a high purity Ge coaxial cylinder 44 mm in diameter and 41 mm in length, with an efficiency of 10% at 1.33 MeV relative to a 7.6 × 7.6 cm NaI(Tl) crystal for a point source at 25 cm. It is mounted in a small liquid nitrogen dewer that features an all-attitude capability. The spectrum is collected in a portable multichannel analyzer that also provides high voltage and preamplifier power to the detector. The first analysis of the spectra can be performed in a portable computer connected to the multichannel analyzer with the use of home-made software. The measurements were performed (during 1998) with a tripod-mounted, downward-

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facing detector at 1 m above the soil surface in twelve randomly distributed locations of the experimental plot area (2,000 m^2) of the University experimental forest of Taxiarchis Chalkidiki in Northern Greece. The description of the ecosystem as well as the mean soil and basic stand characteristics can be found in a recent publication (Antonopoulos-Domis et al. 1997).

In order to deduce the relative contribution of ^{137}Cs to the total gamma dose rate in air one has to determine separately a) the total gamma dose rate in air due to natural radioactivity and ^{137}Cs, the only gamma emitter still important from the Chernobyl accident; and b) the gamma dose rate in air due only to ^{137}Cs.

A recent spectral stripping method (Clouvas et al. 1998) for the determination of the total gamma dose rate in air was applied to the *in-situ* spectra. This method does not require any assumptions concerning the source geometry. The first spectral stripping method for portable Ge detectors was introduced by Miller and Beck (1984). A summary of the procedure is presented here. The complete description can be found in the aforementioned corresponding publications. A count registered by the detector can be caused by the full or partial absorption of an incident photon or by the passage of a cosmic ray producing a charged particle. In order to convert to gamma dose rate, the spectrum must be stripped from the partial absorption and cosmic ray events leaving only the events corresponding to the full absorption of a gamma ray. The resulting spectrum, which represents both primary as well as scattered photons, can then be converted to the total incident flux spectrum by applying the full absorption efficiency curve $\epsilon(E)$ of the detector (Fig. 1), which has been determined (Clouvas et al. 1998) by calibrated point sources and Monte Carlo simulations. Having deduced the flux energy distribution $\Phi(E)$ the absorbed dose rate in air due to gamma radiation can be easily calculated:

$$\dot{D}_t = \sum_{i=1}^{N} \Phi(E_i) \times E_i \times \mu(E_i), \quad (1)$$

where $\dot{D}_t$ is the absorbed dose rate in air, ΦE is the incident photon flux of energy E, μ is the mass absorption coefficient for air at energy E.

The summation starts at Energy E_1 = 50 keV (practical lower energy limit of our detector due to electronic noise and reduced efficiency), proceeds with a step ΔE_i = 0.4 keV (determined mainly by the amplifier gain and the number of channels of the MCA), and ends at E_N = 3,000 keV (the highest energy gamma line is at E = 2,615 keV).

For the determination of the gamma dose rate in air due only to ^{137}Cs, the following steps were followed:

1. By the *in-situ* gamma spectra and particularly from the ^{137}Cs photopeak, the dose rate in air due to unscattered photons (around 661.6 keV) can be easily deduced from eqn (2):

$$\dot{D}_{unsc} = E \times (A/\epsilon) \times \mu(E), \quad (2)$$

where $\mu(E)$ is the mass absorption coefficient for air at E = 0.661 MeV, A is the number of counts in the photopeak per unit of time (in counts per minute), and ϵ is the peak count rate (in counts per minute) per unit uncollided flux (photons cm^{-2} s^{-1}) for a parallel beam of gamma rays of energy E = 0.661 MeV that is incident—normal to the detector face. The full absorption peak efficiency, ϵ, for parallel incident flux at energy E = 0.661 MeV has been determined with the use of a ^{137}Cs point source of known activity. In field gamma spectrometry measurements the incident gamma

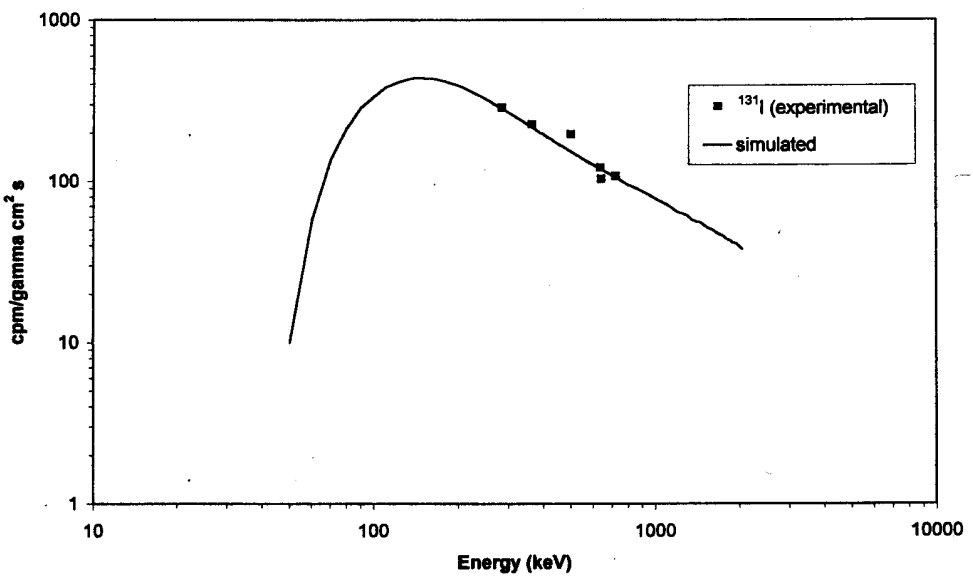

Fig. 1. Detector efficiency as deduced by point sources and Monte Carlo simulations (Clouvas et al. 1998).

radiation is not just a parallel flux normal to the detector face but has all angles of incidence. However, it has been shown (Clouvas et al. 1998) that the angular response of the detector is not a critical factor, and within 5% it can be considered that the Ge detector has a uniform response over angles at least up to 120° of incidence; and

2. Once the $\dot{D}_{unsc}$ is determined the total dose rate in air $\dot{D}_{Cs}$ due to scattered and unscattered gamma radiation from ^{137}Cs deposited in the ecosystem can be deduced if the dose rate in air $\dot{D}_{scatt}$ due to scattered radiation is known. Unfortunately, it is impossible to deduce from an *in-situ* gamma spectra the scattered radiation from a specific radionuclide. Even if a spectral stripping method is performed, the continuum in the *in-situ* spectra is a superposition of scattered radiation from different gamma emitters present at the site. Therefore, another method is necessary to determine the ratio of the unscattered to scattered radiation in the specific site. This can be done by Monte Carlo simulations if the distribution of ^{137}Cs to the different parts of the ecosystem is known. Using as input the results of the radiocesium distribution in the different parts of the ecosystem determined recently (Antonopoulos-Domis et al. 1997), Monte Carlo simulations were performed using the MCNP code (Briesmeister 1993) in order to deduce the so called Build up factor B:

$$B = \dot{D}_{Cs}/\dot{D}_{unsc} \quad (3)$$

$$\dot{D}_{Cs} = \dot{D}_{unsc} + \dot{D}_{scatt}. \quad (4)$$

Deducing B from the simulations and $\dot{D}_{unsc}$ from the *in-situ* spectra the total dose rate due to radiocesium deposited in the ecosystem can be easily calculated.

RESULTS AND DISCUSSION

Calculation of the ratio *B* by Monte Carlo simulations

The simulations were performed with the MCNP code executed on a standard PC Pentium at 266 MHz computer. The Los Alamos National Laboratory MCNP code is a general-purpose Monte Carlo radiation transport code that can numerically simulate neutron, photon, and electron transport. For photons, the code takes account of incoherent and coherent scattering, the possibility of fluorescent emission after photoelectric absorption, absorption in pair production with local emission of annihilation radiation and bremsstrahlung.

The user-supplied information required by MCNP contains information about specific items such as the geometry and the materials characterizing the environment that will be simulated, the source distribution of the radiation, and finally the type of the answers desired (e.g., energy distribution of photon flux in a given position).

The simulated geometry of the forest ecosystem as introduced in the MCNP code is shown in Fig. 2. The different components of the ecosystem incorporated in the simulation are as follows:

- *Forest Floor*: Simulated as a cylinder of 40 m radius and 3 cm height with an atomic composition of 54% C, 38% O, 5% H, 1.5% Si, 1.5% N and a density of 0.25 g cm^{-3}. The radius of 40 m was found sufficient in order to consider the emission photon geometry as half space geometry;
- *Ah soil layer*: Located beneath the forest floor and simulated as a cylinder of 40 m radius and 1 cm height with an atomic composition of 23% C, 28% O, 9% H, 30% Si, 10% Al and a density of 0.61 g cm^{-3};
- *Soil*: Simulated by eight overlaid cylinders of 40 m radius and 5 cm height each. The density of each soil layer has been measured *in-situ* in the forest (ranging from 0.8 to 1.5 g cm^{-3}) and has been presented in a recent publication (Antonopoulos-Domis et al. 1997). The atomic composition of the soil introduced in the Monte

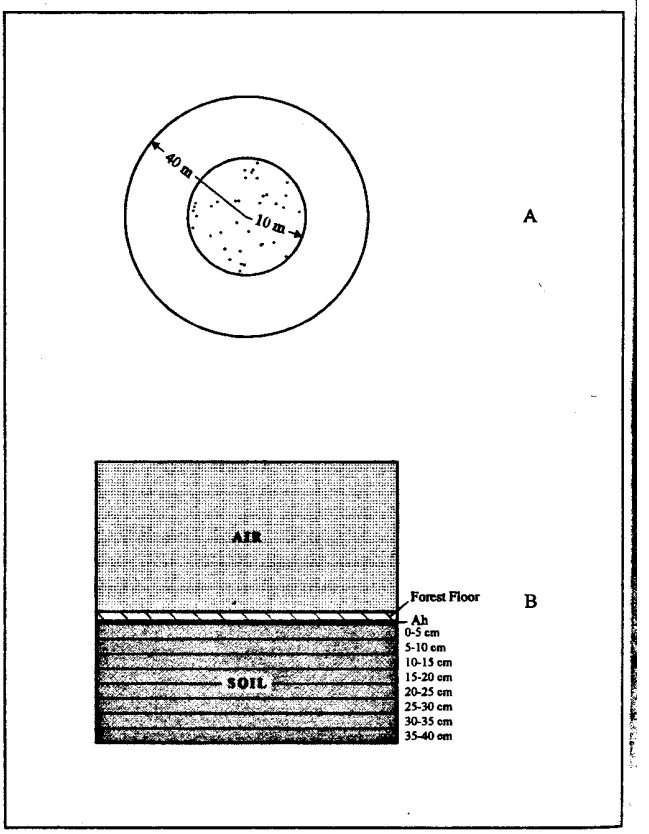

Fig. 2. Model of the forest site as simulated by the MCNP code. Part A is a plane view. The points are the locations of the trees randomly distributed inside a circle of radius 10 m. In part B is shown a section view. The structure beneath the forest floor is cylindrically symmetric.

Carlo code is 50% O, 31% Si, 6% Al, 6% H, 2% Fe, 2% C, 2% Ca, 1% K;

- *Trees*: Trees may be important in the gamma dose rate estimations as they may attenuate the radiation field through shielding and may also serve as a source of radiation from any activity contained within the tree biomass. The mean number of stems per 1,000 m^2, the mean breast diameter, and height of the trees are known from previous studies (Antonopoulos-Domis et al. 1997). According to these results the number of trees which have to be included in the simulation (corresponding to a circle surface of 40 m radius) is 592. In order to reduce this number it was assumed that only trees inside a circle surface of 10 m radius are important. This is true if one considers that 84% of the radiation comes from the zone inside the 10 m radius (Helfer and Miller 1988). The location of the 37 trees (corresponding to a circle surface of 10 m radius) were randomly distributed. The woods were simulated as cylinders of 10 cm radius and 10 m height with an atomic composition of 55% C, 30% O, 12% H, 3% Si and a density of 0.61 g cm^{-3}; and
- *Air*: Atomic composition of 79% N, 21% O.

Fifty million photons (661.6 keV) were emitted from all mentioned above parts of the forest ecosystem (except air) with a percentage contribution deduced from a recent study of the distribution of ^{137}Cs in the specific ecosystem (Antonopoulos-Domis et al. 1997). Table 1 presents the percentage contributions of photon emission from the different parts of the ecosystem as deduced from that study. The total measured amount of ^{137}Cs in the ecosystem during 1995 was 24.3 ± 6.6 kBq m^{-2}, which extrapolated to 1998 gives 22.7 kBq m^{-2}. It can be seen from Table 1 that the contribution of photon emission from all trees is 2% of the total photon emission from all parts of the ecosystem. Taking into account that in the simulated geometry we located trees only within a circle surface of 10 m radius instead of 40 m radius (37 trees instead of 592), the contribution of photon emission from the 37 trees is reduced to 0.12% of the photon emission from all parts of the ecosystem and therefore can be neglected.

Table 1. ^{137}Cs distribution in the ecosystem as measured in 1995 (Antonopoulos-Domis et al. 1997).

	^{137}Cs (MBq ha^{-1})	Contribution (%)
Soil		
Layer		
Ah	128 ± 59	52.60
0–5	57 ± 25	23.40
5–10	12 ± 6.8	5.00
10–15	3.3 ± 1.8	1.30
15–20	2 ± 0.2	0.80
20–25	1.5 ± 1.29	0.53
25–30	0.9 ± 0.32	0.33
30–35	0.6 ± 0.23	0.20
35–40	0.9 ± 0.43	0.20
Sub-total	206 ± 65	84
Forest floor	32.6 ± 9	13.40
Ground vegetation	0.016 ± 0.007	0.006
Biomass		
Trunk	1.29 ± 0.6	0.53
Bark	1.23 ± 0.3	0.50
Leaves	0.16 ± 0.08	0.065
Branches		
<1 cm	0.19 ± 0.06	0.078
1–3 cm	1.13 ± 0.8	0.40
3–6 cm	0.90 ± 0.5	0.37
>6 cm	0.80 ± 0.4	0.33
Sub-total	5.70 ± 1.03	2.27
Total	243.00 ± 66	100.00

For the determination of the photon flux energy distribution at 1 m above the forest floor, from which the *B* ratio was deduced, the point detector was used, which is a standard tally of the MCNP code. This tally gives the energy distribution of the photon flux directly, normalized per starting photon. In addition, a particle detector was used that counts the number of photons as a function of their energy crossing a surface of a sphere of radius of 40 cm located at 1 m above the forest floor. Both virtual detectors are located in the Z axis of the cylinder of radius of 40 m.

The number of photons as a function of their energy counted by the particle detector is given in Fig. 3. The calculations were performed with an energy step of 10 keV. The number of photons recorded in each step is statistically satisfactory (about 9,000 photons for the unscattered radiation and 100–400 for the scattered radiation). The expected peak at 200 keV originated from backscattered photons in the forest floor, Ah and the upper soil layers, can be observed in the simulated spectra.

The simulated flux per 10 keV step as calculated for the point detector for a total ^{137}Cs deposition of 24 kBq m^{-2} is shown in Fig. 4. The error in the simulated flux is less than 2%. However one has always to keep in mind that this error refers only to the precision of the Monte Carlo calculation itself and not to the accuracy of the result compared to the true physical value.

From the photon flux energy distribution (Fig. 4) the build up factor is easily deduced from eqn (5) to be equal to 1.4:

$$B = \sum_{i=1}^{N} E_i \times \Phi(E_i) \times \mu(E_i)/E_N \times \Phi(E_N) \times \mu(E_N), \quad (5)$$

where E_i is the average energy of band i, $\Phi(E_i)$ is the flux incident in energy band i, and $\mu(E_i)$ is the average mass absorption coefficient for air at energy band i.

The summation starts at the energy band $i = 1$ (0–10 keV) proceeds with a step of 10 keV and ends at the energy band $i = N$ containing the energy of 661.6 keV.

It should be noted that the determination of the factor B from eqn (5) does not require any knowledge of the total radiocesium deposition in the ecosystem but

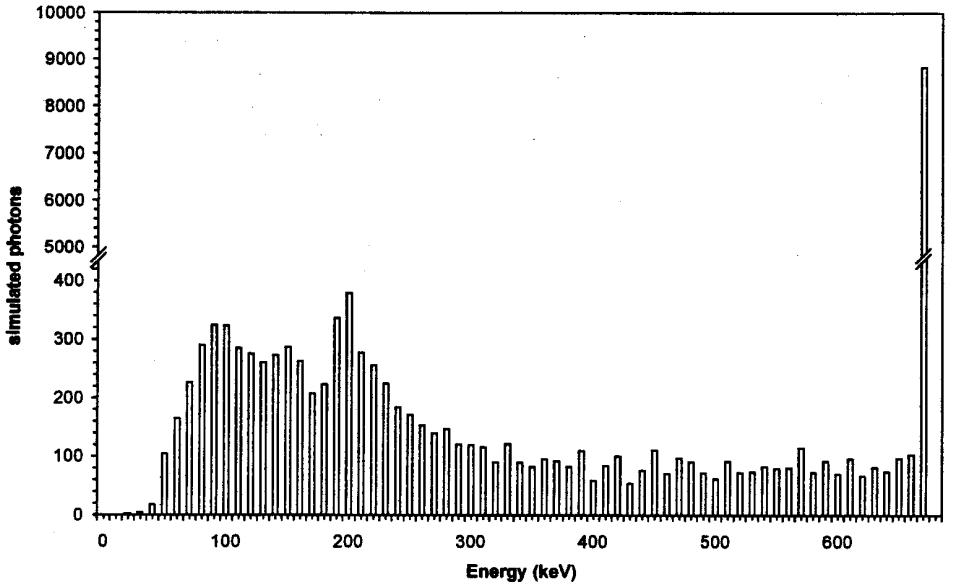

Fig. 3. Number of photons crossing a sphere of radius 40 cm and located 1 m above soil surface as deduced from the Monte Carlo simulations for a total emission fifty million photons from all parts of the ecosystem. The calculations were performed with an energy step of 10 keV.

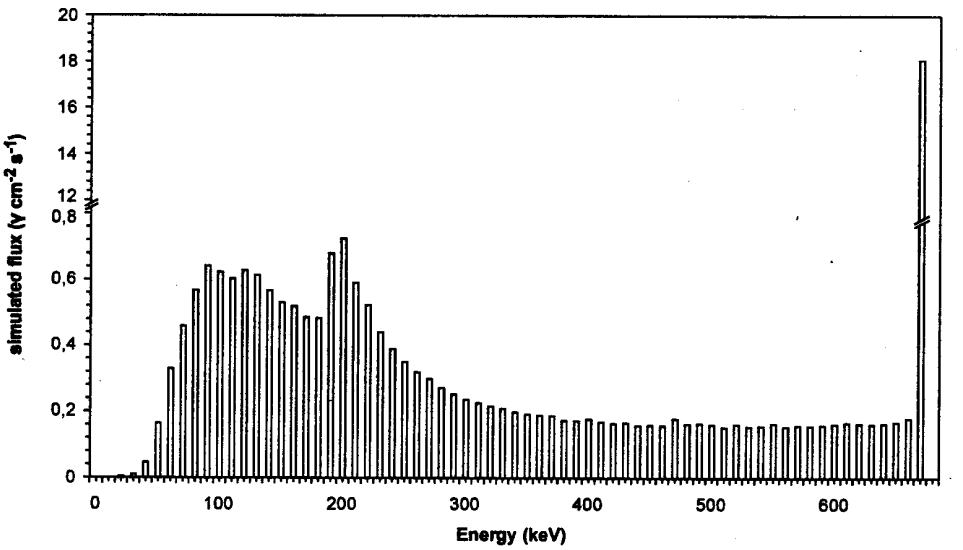

Fig. 4. Photon flux at 1 m above soil surface as deduced from the Monte Carlo simulations for a total ^{137}Cs deposition of 24 kBq m^{-2}. The calculations were performed with an energy step of 10 keV.

only the relative contributions of the photon emission from the different parts of the ecosystem. If the total radiocesium deposition is known, from the numerator of eqn (5), in principle one can directly calculate the absorbed dose rate in air due only to radiocesium without the need to perform an *in-situ* gamma spectrometry measurement and to use eqns (2) and (3). However, even if the radiocesium deposition in the ecosystem is precisely known, one has to be very careful in using the direct calculation and not the build up factor method. This is due to the fact that the absolute flux values are strongly dependent on the density of materials used in the simulation (a precise knowledge of the *in-situ* density of forest floor, Ah, soil is needed). On the contrary, the Build up factor B depends slightly on the density of the different parts of the ecosystem. This is impressively

shown in the following numerical experiment, where radiocesium is assumed to be uniformly distributed in soil of radius 40 m and depth 1 m. With the MCNP code, the Build up factor B and the unscattered flux 1 m above soil for 5 different soil densities (0.5–2 g cm^{-3}) were calculated. The results are normalized for the density of $\rho = 1$ g cm^{-3} and presented in Table 2. It is clear from Table 2 that the unscattered flux is strongly dependent on the density (ρ^{-1}), while B has a weak dependence on the density.

Contribution of ^{137}Cs to the total external gamma dose rate in air

In order to determine the total gamma dose rate in air due to natural gamma emitters and ^{137}Cs from the Chernobyl accident, two *in-situ* gamma spectroscopy measurements of 8,000 s each, and 10 measurements of 2,000 s each have been performed during 1998 in different locations of the experimental area.

A long-term (8,000 s) typical *in-situ* gamma spectrum is shown in Fig. 5 where the pronounced peak at 661.6 keV due to ^{137}Cs from the Chernobyl accident can be seen. Applying the stripping operation (Clouvas et al. 1998) to the spectrum, about 50% of the counts are removed. These counts are removed from the continuum portion of the spectrum, while the peaks due to the full absorption of the primary flux are preserved. The stripped spectrum of Fig. 5 is converted to incident flux by applying the full absorption efficiency of the detector given in Fig. 1. The flux energy distribution thus computed is shown in Fig. 6. The total absorbed dose rate in air $\dot{D}_t$ can then be easily calculated from eqn (1) and was found to be 64 nGy h^{-1}. From the ^{137}Cs photopeak the dose gamma rate in air $\dot{D}_{unsc}$ due to unscattered photons was calculated from eqn (2) and found to be equal to 18 nGy h^{-1}. Multiplying this value with the Build up Factor $B = 1.4$ deduced from the Monte Carlo simulations the absorbed dose gamma rate in air due to ^{137}Cs is $\dot{D}_{Cs} = 25$ nGy h^{-1}, which is about 40% of the total absorbed gamma dose rate in air. This contribution is important as a percentage, if one takes into account that in urban areas in Greece the contribution of ^{137}Cs to the total gamma dose rate in air is always less than 15%. The difference between $\dot{D}_t$ and $\dot{D}_{Cs}$ is the absorbed dose rate in air $\dot{D}_N = 39$ nGy h^{-1}, due only to natural gamma emitters (uranium series, thorium series, and ^{40}K) and corresponds to the absorbed gamma dose rate in air inside the forest before the Chernobyl accident. The radiocesium contamination of the forest due to weapons fallout is very small (Antonopoulos-Domis et al. 1997), and therefore the radiocesium contamination of the forest before the Chernobyl accident can be neglected.

The same values of $\dot{D}_t = 64$ nGy h^{-1} and $\dot{D}_{unsc} = 18$ nGy h^{-1} have been extracted also from the second long term *in-situ* spectrum. In fact, the two long term (8,000 s) *in-situ* spectra were almost identical. It should be noted that these values are in very good agreement with the values we obtained in 1995 in the same location (Antonopoulos-Domis et al. 1997). The difference in the values of $\dot{D}_{Cs}$ between the two studies is that in the preliminary study a rough estimation for the build up factor was used, which overestimated it. The error in the $\dot{D}_t$ is mainly due to the stripping procedure, which is known to be correct (Clouvas et al. 1998) within 15%. The error in the $\dot{D}_{unsc}$ is normally due to the determination of the counts in the photopeak and to a lesser extent to the precision of the efficiency of the detector. This is true when photopeaks are small. However, in cases as in Fig. 5 where there is a pronounced photopeak, the error in the determination of $\dot{D}_{unsc}$ is mainly due to the precision of the efficiency of the detector. The error in the $\dot{D}_{Cs}$ is due to the reasons mentioned for $\dot{D}_{unsc}$ and indeed to the error of the simulation procedure for deducing the Build up factor B. As mentioned in the previous section the error in the simulated flux is less than 2%. However, one has always to keep in mind that this error refers only to the precision of the Monte Carlo calculation itself and not to the accuracy of the result compared to the true physical value. From the simulated unscattered flux (Fig. 4) at 661.6 keV for a total ^{137}Cs deposition of 24 kBq m^{-2} measured (by laboratory gamma spectroscopy) in all parts of the ecosystem during 1995 a $\dot{D}_{unsc}$ value of 20 nGy h^{-1} can be deduced. Correcting this value for radioactive decay, a value for 1998 of 18.7 nGy h^{-1} can be deduced, which is within 3.9% of the measured value of 18 nGy h^{-1} deduced by *in-situ* gamma spectrometry measurements. This clearly indicates that the Monte Carlo simulation used gives very good results at least for the unscattered radiation.

In order to estimate the spatial variability of $\dot{D}_{Cs}$, 10 short-term (2,000 s each) *in-situ* gamma spectroscopy measurements were performed during 1998 in different locations of the experimental plot area. The results from these measurements as well as from the two long-term measurements (8,000 s) are shown in Fig. 7, where the numbers indicate the absorbed gamma dose rate in air $\dot{D}_{Cs}$ in nGy h^{-1}. Within the experimental uncertainty (15%) a uniform spatial distribution of $\dot{D}_{Cs}$ can be assumed.

The mean value from these 12 *in-situ* gamma spectrometry measurements is $\dot{D}_{Cs} = 22$ nGy h^{-1}. Correcting the value of the total ^{137}Cs deposition measured in 1995 (Antonopoulos-Domis et al. 1997) in all parts of the ecosystem for physical decay, the total deposition in 1998 was deduced as 22 kBq m^{-2}. From this value and the value of $\dot{D}_{Cs} = 22$ nGy h^{-1} a conversion factor $C = 1$ nGy h^{-1}/kBq m^{-2} can be deduced for ^{137}Cs. This

Table 2. $\dot{D}_{unsc}$ and B factors for different soil densities as deduced from the Monte Carlo simulations. The values are normalized to the values obtained with soil density of 1 g cm^{-3}.

g (g cm^{-3})	$\dot{D}_{unsc}$ (normalized)	B (normalized)
0.5	2	1.08
1	1	1
1.3	0.77	0.98
1.5	0.67	0.98
2	0.5	0.98

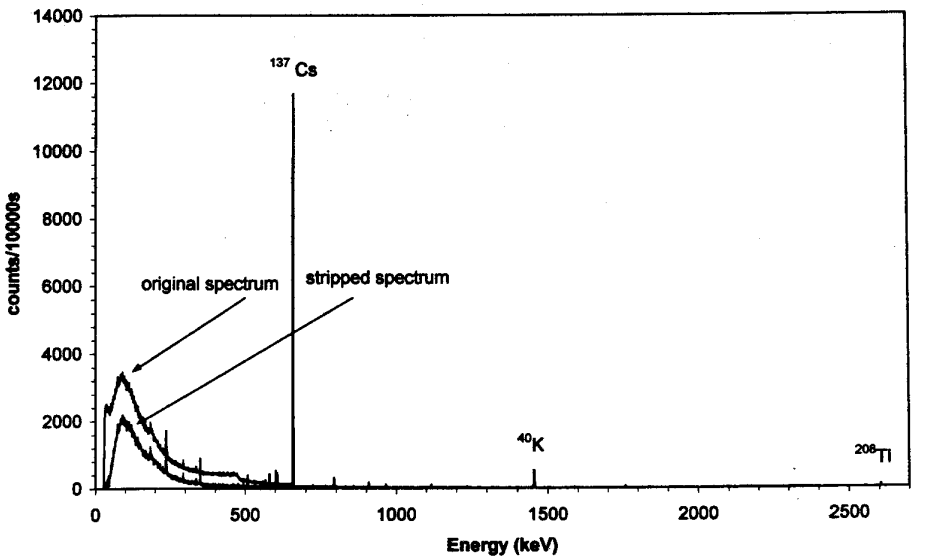

Fig. 5. *In-situ* gamma ray spectrum inside the forest before and after stripping operation. After stripping operation about 50% of the counts are removed. These counts are removed from the continuum portion of the spectrum, while the peaks are preserved. The pronounced peak at 661.6 keV due to ^{137}Cs from the Chernobyl accident can be seen.

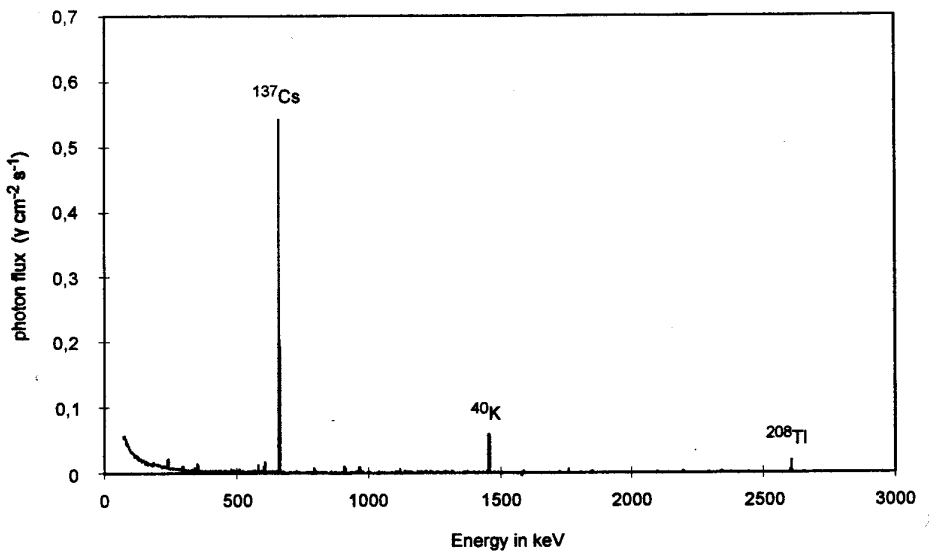

Fig. 6. Photon flux spectrum (γ cm^{-2} s^{-1}) 1 m above ground.

factor must be used with caution and only for forest sites similar to the one used for this work.

CONCLUSION

The absorbed gamma dose rate in air at 1 m above soil due to natural gamma emitters and ^{137}Cs from the Chernobyl accident was determined inside a Quercus conferta Kit ecosystem in Northern Greece by combination of Monte Carlo simulations with the MCNP code and *in-situ* gamma spectrometry measurements. The following conclusions are noted:

- The total absorbed gamma dose rate in air is about 64 nGy h^{-1}, where 40% of this value is due to ^{137}Cs and 60% to natural gamma emitters. The 40% contribution is important as a percentage, if one takes into account that in urban areas in Greece the contribution of ^{137}Cs to the total gamma dose rate in air is always less than 15%;

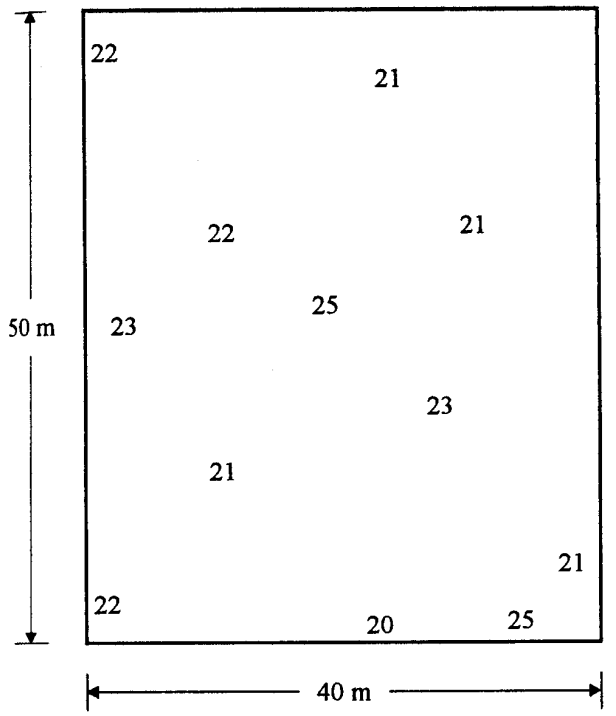

Fig. 7. Location of the 12 *in-situ* gamma spectroscopy measurements performed inside the experimental plot area. The numbers indicate the absorbed gamma dose rate in air (in nGy h^{-1}) due to ^{137}Cs.

- The Monte Carlo simulations indicated that the gamma absorbed dose rate in air due to ^{137}Cs is mainly due (70%) to the unscattered radiation and to a lesser extent (30%) to the scattered radiation. The results obtained with the Monte Carlo simulations for the unscattered radiation were in very good agreement with the experimental values deduced by *in-situ* gamma spectrometry measurements; and
- From the combination of the Monte Carlo simulations and *in-situ* gamma spectrometry measurements a conversion factor $C = 1$ nGy h^{-1}/kBq m^{-2} was deduced for ^{137}Cs. This factor must be used with caution and only for forest sites similar to the one used for this work. However, it would be interesting to determine this factor for a completely different forest ecosystem, e.g., pine forest.

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