EMRAS-II WG7 Tritium Accidents

Spatial variability of tritium re-emission, review of soil-plant models and development prospects

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1. Introduction

The soil-plant system is considered in this section from a prospective of handling spatial variability in tritium re-emission, perceived as a key constituent of uncertainty in hydrology. Subsequent review of soil-plant modules is performed on the example of four typical models of significantly different complexity, which are currently in use. The focus is made on their functionality pertaining to possibility to deploy them in the future attempt to address spatial variability in tritium transfer. Models considered are GAZAXI (CEA), ETMOD (AECL), UFOTRI (KIT) and SOLVEG-II (JAEA). Analysis of soil module of these models is put into the context of generic structure of typical operational land surface scheme (LSS) dealing with soil-plant-atmosphere exchange and components of surface water and energy balance and having close affinity to analyzed tritium transfer models. The latter are also grouped with respect to processes modelled.

The soil-plant system provides tritium re-emission, lets tritium through (thus making a tritium sink) and also stores some amount of tritium causing certain lag in both re-emission and loss. Tritiated water vapour from atmospheric release (HTO) moves with water and follows water cycle in soil-plant-atmosphere system. HTO also diffuses on its own according to the concentration gradient. Transfer of tritium gas (HT) is subject to the same rules as independent HTO diffusion. However, HT consideretion here is omitted on the assumption of HT undergoes fast transformation into HTO with once in contact with the soil layer due to microbial activity. No further consideration to HTO could be given on the assumption of a known rate of HT to HTO transformation. By means of independent diffusion and transport with water (which is comprised of diffusion and advection processes) HTO is supplied into green parts of vegetation, mostly leaves, where it is bound into carbohydrates by photosynthesis and so forms OBT.

We limit ourselves to one-dimentional case where water enters and leaves the soil-plant system through openings in leaves (stomata and cuticles), through pores in soil and through the bottom layer of soil (deep aquifer discharge and recharge via drainage). Water also leaves the system via runoff, which is specified in one dimension as point and line sinks due to loss to surface runoff and to sub-surface lateral flow correspondingly. Diffusion of tritium is also assumed one-dimensional.

2. Objective

The overall goal of EMRAS-II is to diminish ucertainties associated with environmental variability of tritium transfer processes. In our case soil-plant interaction is subject to:

- Spatial variability caused by differences in soil texture, land use, etc.;
- Temporal variability from meteo-forcings
- Inter-species, or cultivar variability

Variability makes model validation limited and existing models appears universally applicable only at a cost of large uncertainties. It is understood, that presently the ranking of sources of variability has a high degree of subjectivity. With this in mind, we tend to rely on historical and recent experimens at CRL, which allow assume inter-species (cultivar) variability being mostly smaller than variability in space and in time and on these grounds cultivar analysis is proposed to be addressed in the future.

In this section we approach the important aspect of spatial variability using the signature of resulting surface fluxes, propose approach to spatial variability handling and address associated part of temporal variability.

3. Coupling of atmosphere to soil and three generations of land surface schemes

Modelling systems devoted to soil-plant-atmosphere interactions play the role of dynamical boundary conditions on the bottom of atmosphere required for larger weather prediction system (global circulation model). For this reason the soil-plant-atmosphere systems are called land surface schemes. These schemes are required to be robust and universally applicable and today we face the third generation LSS progressing. Traditionally tritium models either follow LSS, or are directly imbedded into these schemes. Spatial variability is therefore proposed to treat from the standpoint of energy budget analysis, traditional in weather prediction modelling.

The partitioning between re-emission and losses to sinks and the size (and role) of the soil-plant system depot are presently a subject of ongoing research. The major reason is the absence of clarity in land surface classification with respect to partitioning of surface fluxes between sensible and latent heat The latent heat is also known as evapotranspiration and provides a route of tritium re-emission. In some situations partitioning could be simply defined (and parameterized) at the surface; one of the concepts is known as a bucket model, deploying the virtual bucket to represent the soil considered as a single slab. Precipitation (storm) exceeding the size of the bucket simply cause the bucket to overflow thus simulating the surface runoff. Modifications like leaking bucket for known drainage rates are also often encountered. The problem, however is that in certain other situations the apparent feedback occurs in the soil-atmosphere system and this feeback is known as coupling. If the concept of bucket is retained, large uncertainties occur in the case of strong coupling. The bucket approach is so termed the firtst generation of land surface schemes, as coupling requires more detail in the soil-plant-atmosphere system. The minimum set of these detail is reflected in typically three soil layers and one- or two-layer canopy (big-leaf approach). Models of this level of complexity were called the second generation and (as they now much better represented surface energy budget components partitioning) were deployed for climate change analysis. The latter purpose urged the inclusion of carbon cycle and photosynthesis in particular and so made them immensely usefull for tritium studies. Many tritium models fall into the category of second generation schemes.

Notwithstanding the progress made, the second generation models did not appear to be universally applicable, as the coupling associated with transition to limited soil water supply seemingly required elaborate parameterization of soil water feedback on ET (in the first place) and on other processes like photosynthesis. Third generation models development was subsequently started about two decades ago and this process is on-going as the progress turns out to be marginal. Third generation is characterised by inclusion of such processes as soil and leaf thermodynamics, plant phenomenology (quite helpful for handling tritium translocation), phase transitions between water vapour and liquid water in soil pores and multiple layers in soil and in canopy. Third generation tritium models built into the framework of third generation land surface shemes inherit very large uncertainties associated with model predictions.

4. Spatial variability of coupling as a basis of robust tritium modelling

It is important to note that coupling is known to be weak in the vicinity of valleys and on flatlands with sufficient frequency and amount of precipitation. Coupling also vanishes on highlands with deep water table and in semi-arid climate. The development of tritium models subsequently can follow two routes. First one could be revision of simple models sophisticated only to serve peculiarities of behaviour of tritiumj per se; this is appropriate where coupling is weak. The second route could be in application of research-grade models to sensitivity analysis of critical zones where coupling is strong. Identification of possibly narrow (Rihani et. al, 2010 and references therein) critical zones responsible for strong coupling shall be left to weather and climate prediction science, where the interest of research community to this subject is already very strong.

5. Addressing temporal variability

We can address now a certain fraction of temporal variability as well, since identification of critical zones and their extent could be performed both in space and in time. Once identified classification of land and also weather regimes (e.g. transition within dry spell) could be performed using shape of critical zones. It seems logical to apply robust but different soil-plant tritium algorithms in the wet and dry regions divided by critical zones. This will address both spatial and temporal variability and diminish associated uncertainties. Experimens at CRL allows assume inter-species (cultivar) variability being smaller than that in space and time and on these grounds cultivar analysis could be deferred.

6. Review of functionality of soil-plant tritium modules

Objective outlined above entitles us to provide the overview of capabilities of existing models of tritium transfer in soil-plant system and outline the approach to spatial variability.

6.1. Processes in soil-plant system

Processes important in the soil-plant system are

- Water Infiltration (HTO advection):
- Storm (Green-Ampt, numerical Richards)
- Free (Darcian flow)
- Root uptake via plant transpiration
- Diffusion of HTO
- Soil Thermodynamics

6.2. Boundary conditions for HTO transfer in the soil-plant system

Boundary conditions for HTO transfer in the soil-plant system

- Independent surface gaseous deposition
- Rainfall, irrigation and dew-fall (assisted transport to soil)
- Re-emission (independent loss to atmosphere according to gradient of concentration)
- Evaporation-assisted transport to atmosphere
- Drainage to aquifer (recharge/discharge)

6.3. Model Capabilities

Model capabilities are summarized according to the list of boundary conditions and processes listed above.

6.3.1. GAZAXI of CEA

GAZAXI is a first generation model in terms of LSS discussed above. It is presented here in order to emhasize the possiboility to use the simplest model of this kind in case they are properly put into the context of spatial variability. The model is formulated in terms of the solution to dynamical exchange processes (Belot equation) rather than in terms of equations per se. However for coherence and ease of comparison with other models, we present the GAZAXI model here in terms of key constituent of these (ommitted) equations, namely the exchange velocity, which once inserted into dynamic equation and after integration gives Belot equation. Exchange velocity implicit to GAZAXI is assumed constant and proportional to leaf area index.

B.cond.: wet (Chamberlain), dry - gradient exchange by Vex~LAI;

Processes: root uptake via ET=const

6.3.2. ETMOD of AECL

ETMOD is a second generation model. ETMOD deploys semi-analytical approach to infiltration. Exchange velocity and ET are both based on resistance approach. Wet deposition is omitted in ETMOD.

B.cond.: only dry (Vex. by resistance approach);

Processes: root uptake via ET (resistance approach),
Diffusion and infiltration – semi-analytical (bottom - no flow),

6.3.3. UFOTRI of KIT

UFOTRI is the other second generation model, which is included into this comparative review because of its performance in soil is superior to that of ETMOD. Evapotranspiration driving tritium re-emission in UFOTI is defined by Monteith formula. Soil infiltration is based on matrix force based on suction tension and hydraulic conductivity:

B.cond.: wet (scavenging coeff), dry (Vex. by resistance approach),
re-emission ~ ET (Monteith);

Processes: root uptake via ET (Monteith),
infiltration – matrix force (suction tension, h. conductivity,
bottom - no flow);

6.3.4. SOLVEG-II

SOLVEG-II is presently the most elaborate example of generation three models. It accounts for two phase dynamics of water (water vapour and liquid water) in soil pores, it accounts for Simunek-Suarez dynamics of CO2 in soil and it provides the partitioning critical for translocation of carbohydrates (and subsequently OBT) in the soil-plant system. SOLVEG-II uses multiple layers of soil, which allows much closer capture of actual scale of tritium transfer processes. It is very important to mention, that SOLVEG was used in operational mode in a coupled model with the hydrological block, which makes the model perfectly fit for the study of sensitivity of tritium re-emission to spatial variability in general and to topography (suggested by Rihani et. al, 2010) in particular.

B.cond.: wet (scavenging coeff),
mixed b.c. (Vex., carbon-modelled stom. resistance),
re-emission independently via Vex and carbon-based ET;

Processes: Soil thermodynamics,
CO2 diffusion,
2-phase HTO diffusion and advection (1-phase Richards for water)

7. Proposed approach integrating the use of analysed models

The third-generation model could help resolve the question of sensitivity of tritium transfer to degree of coupling of atmosphere to soil. Tritium re-emission is directly driven by the latent heat flux and sensitivity of tritium re-emission to coupling is expected to be high. SOLVEG-II is presently the best candidate model for sensitivity test, as SOLVEG-II has an option of a coupled run with a 3D hydrological module and thus is directly applicable to analysis of critical zones, where strong atmosphere-soil coupling occurs.

Comparison with simpler models (first generation GAZAXI, second generation models e.g. UFOTRI, ETMOD, etc.) is recommended. Either empirical or experimental (polynomial fit) dependence of canopy conductance on soil water availability could be implemented for adjustment of deposition velocity of these models. For example, experimental data of Granier et al. (2000) is presented on Figure 5:

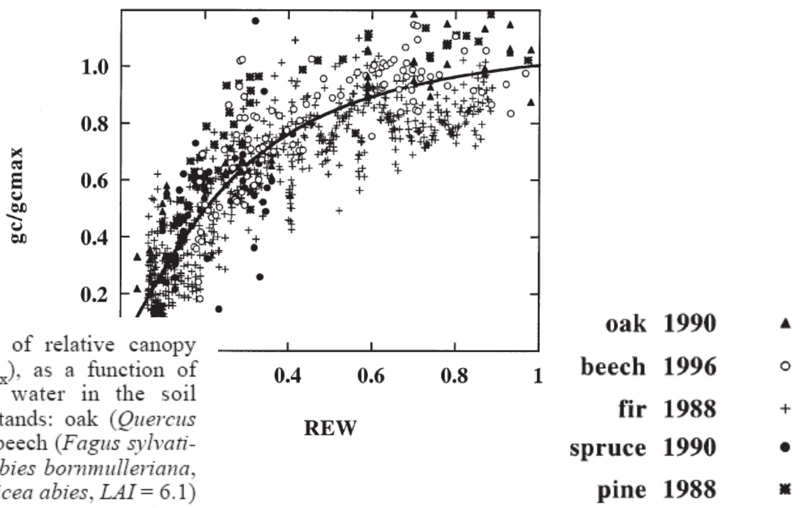
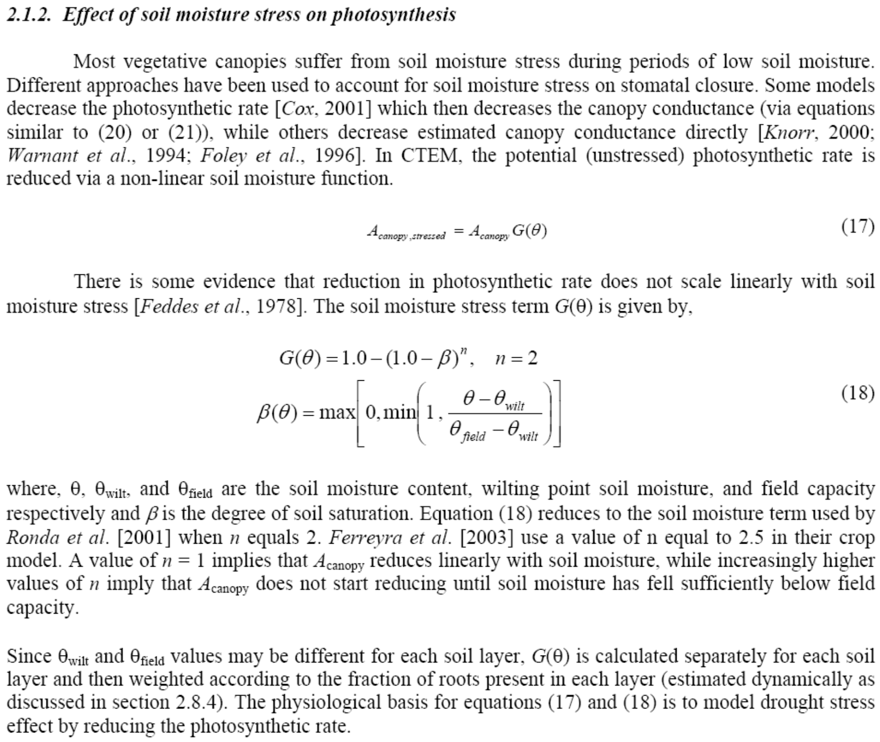


Figure 5. Variation of relative canopy conductance (g_c/g_{cmax}), as a function of relative extractable water in the soil (*REW*) in 5 forest stands: oak (*Quercus petraea*, *LAI* = 6.0), beech (*Fagus sylvatica*, *LAI* = 5.8), fir (*Abies bornmulleriana*, *LAI* = 8.9), spruce (*Picea abies*, *LAI* = 6.1) and pine (*Pinus pinaster*, *LAI* = 2.7). In oak, beech, spruce and pine, g_c is related to modelled g_{cmax}. In fir, g_c is related to g_{cmax} measured in a well-watered plot. A unique relationship was drawn.

Adjustment of OBT production based on photosynthetic activity accounted in second generation models could be performed on the basis of non-linear function of soil moisture (Arora, 2003 and references therein).



2.1.2. Effect of soil moisture stress on photosynthesis

Most vegetative canopies suffer from soil moisture stress during periods of low soil moisture. Different approaches have been used to account for soil moisture stress on stomatal closure. Some models decrease the photosynthetic rate [*Cox*, 2001] which then decreases the canopy conductance (via equations similar to (20) or (21)), while others decrease estimated canopy conductance directly [*Knorr*, 2000; *Warnant et al.*, 1994; *Foley et al.*, 1996]. In CTEM, the potential (unstressed) photosynthetic rate is reduced via a non-linear soil moisture function.

$$A_{canopy,stressed} = A_{canopy}\, G(\theta) \tag{17}$$

There is some evidence that reduction in photosynthetic rate does not scale linearly with soil moisture stress [*Feddes et al.*, 1978]. The soil moisture stress term $G(\theta)$ is given by,

$$\begin{gathered} G(\theta) = 1.0 - (1.0 - \beta)^n, \quad n = 2 \\ \beta(\theta) = \max\left[0, \min\left(1, \frac{\theta - \theta_{wilt}}{\theta_{field} - \theta_{wilt}}\right)\right] \end{gathered} \tag{18}$$

where, θ, θ_{wilt}, and θ_{field} are the soil moisture content, wilting point soil moisture, and field capacity respectively and β is the degree of soil saturation. Equation (18) reduces to the soil moisture term used by *Ronda et al.* [2001] when n equals 2. *Ferreyra et al.* [2003] use a value of n equal to 2.5 in their crop model. A value of $n = 1$ implies that A_{canopy} reduces linearly with soil moisture, while increasingly higher values of n imply that A_{canopy} does not start reducing until soil moisture has fell sufficiently below field capacity.

Since θ_{wilt} and θ_{field} values may be different for each soil layer, $G(\theta)$ is calculated separately for each soil layer and then weighted according to the fraction of roots present in each layer (estimated dynamically as discussed in section 2.8.4). The physiological basis for equations (17) and (18) is to model drought stress effect by reducing the photosynthetic rate.

Some adjustment of first and second-generation models (GAZAXI, ETMOD and UFOTRI) could be performed for two basic cases where the coupling is weak.

7.1. Uncoupled atmosphere, Case 1:

This case corresponds to situation where water supply is ample and latent heat (ET) and sensible heat partitioning favours ET. ET subsequently approaches potential ET (PET) and as such only depends on meteorology – spatial variabilty becomes secondary. The only difference from PET occurs because of stomata blocking in instances of high atmospheric humidity, which should be somehow taken into account possibly via robust parameterization of one of the popular PET formulations. Priestley-Taylor ET formula is the most robust as it depends on a single parameter allowing calibration. Penmann-Monteith ET is more flexible and thus preferable; this however, occurs on expense of dealing with more parameters which should be taken care of. No-flow bottom boundary conditions or the bucket model approach is assumed.

7.2. Uncoupled atmosphere, Case 2:

This case is characterized by water-stressed conductance g_c and ET.
Leaking Bucket could be deployed, free drainage as the bottom boundary conditions are assumed. Some investigation into the role of soil thermodynamics (model sensitivity) could be planned, so that consideration of soil temperature could possibly be substituted for a single value of surface temperature.

7.3. Proposed approach to spatial variability

Complete tritium model could contain the algorithm of mapping of soil texture to digital elevation map and further GIS-based parameterization of HTO re-emission in each grid-cell using a combination of Case 1 and Case 2 HTO re-emission algorithms based on differently defined ET

8. Conclusion

Soil-atmosphere coupling and sfc. fluxes occurs in particular via correlation of surface fluxes and water table depths. Certain range of terrain slopes was shown being responsible for high correlation of this kind (critical zones). Critical zones therefore separate dryer highlands, where the latent heat fux is apparently capped by a limited surface moisture supply and valleys, where the soil moisture allows vegetation operate much closer to potential ET. Variability of surface fluxes within critical zones appreciably exceeds the the variability away from critical zones and so spatial variability could be seen approximated by a contribution from two zones with a constant effective surface fluxes in each (particularly ET) and a third (critical) zone.

9. References

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Coupling groundwater and land surface processes: Idealized simulations to identify effects of terrain and subsurface heterogeneity on land surface energy fluxes

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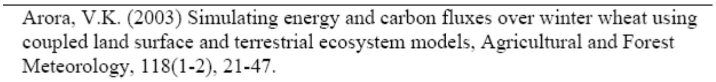

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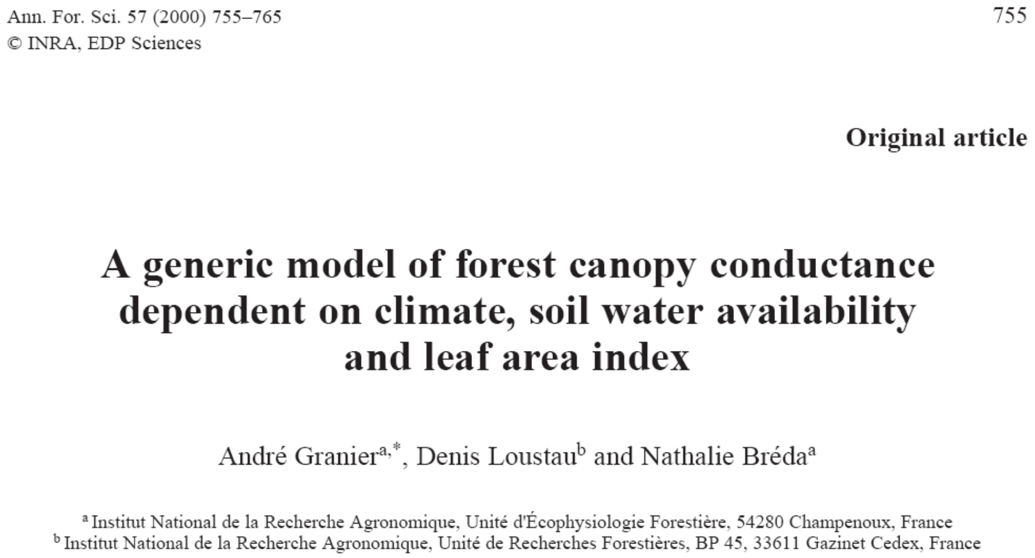

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A generic model of forest canopy conductance dependent on climate, soil water availability and leaf area index

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