

Conclusions

A link between Chameleon and GRASS has been generated, showing how a Web-GIS with analysis functionalities can be easily developed in a fully free and open source environment that guarantee an accessible system, both in terms of coding and costing. Analysis procedures require time to be executed: considering that these tools has been developed for specific users (and not for the mass) the resulting waiting time for the application is acceptable, being in the order of a couples of seconds (to give an idea GrassWatershedPixel processing time to analyse a region of 1492 cols * 1006 rows is 8 seconds and for a region of 604 cols * 652 rows it takes 3 seconds). Because this solution has not been thought to provide a full GIS server service, but just to add specific GIS capabilities to the Web application, in order not to overload the server itself, a restricted users accessing procedure should be considered, as well as other technicals solution like the selection of a limited region for raster analysis used in the application example.

Acknowledgement

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Bibliography

- DM Solution Group (2006) *Chameleon* <http://www.dmsolutions.ca/technology/chameleon.html>
- S. K. Jenson and J. O. Domingue (1988) Extracting Topographic Structure from Digital Elevation Data for Geographic Information Systems Analysis *Photogrammetric Engineering and Remote Sensing* 54 (11): 1593-1600.
- C. Ehlschlaeger (1989) Using the A* Search Algorithm to Develop Hydrologic Models from Digital Elevation Data *Proceedings of International Geographic Information Systems (IGIS) Symposium (Baltimore, MD, 18-19 March 1989)*: 275-281.
- R. Blazek and L. Nardelli (2004) The GRASS Server *Proceedings of the FOSS/GRASS Users Conference 2004 - Bangkok, Thailand, 12-14 September 2004* <http://gisws.media.osaka-cu.ac.jp/grass04/viewpaper.php?id=30>
- J. Y. Choi and B. A. Engel Real-Time Watershed Delineation System Using Web-GIS *Journal Computing in Civil Engineering* 17 (3):189-196
- University of Minnesota (2006) *Mapserver* <http://mapserver.gis.umn.edu>
- HYDRO1k Elevation Derivative Database (2006) *USGS* <http://edcdaac.usgs.gov/gtopo30/hydro/namerica.asp>
- NALCC, North America Land Cover Characteristics (2006) *USGS* http://edcsns17.cr.usgs.gov/glcc/na_int.html
- Hydro demo, watershed analysis demo site (2006) *IST* <http://w3.ist.supsi.ch:8001/geomatica/>
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Simultaneous simulation of hydrological and carbon cycle processes in a GIS framework

Integration of an existing distributed, process-oriented ecosystem model into GRASS GIS in combination with R

by Oliver Sonnentag

Introduction

The application of modeling techniques is a promising and widely used approach to many environmental problems and tasks in academia and industry, especially under circumstances in which direct mea-

surements are not feasible and also for prediction purposes. Process-oriented models simulate physical processes based on fundamental principles, often with some degree of empirical generalization.

The simultaneous simulation of carbon cycle and controlling hydrological processes using a *distributed*, process-oriented ecosystem model such as the Boreal Ecosystem Productivity Simulator (BEPS) developed by Liu et al. (1997, 1999, 2002) is very data-intensive. A variety of software including GIS, remote sensing image processing, and statistical packages has to be employed to pre-process the required input data sets

from different sources, as well as post-process, visualize, and analyze the model outputs.

BEPS has been developed in ANSI C as a stand-alone application on Microsoft's Windows[®] platform. The current version of BEPS contains a graphical user interface (GUI) based on the Microsoft Foundation Class[®] library written in Microsoft's Visual C++[®] (fig. 1). Previous versions of BEPS were executed from the Windows command line and through parameter files. The main purpose of the GUI is to provide a tool that simplifies model parameterization and allows on-screen display of spatial model outputs. As a result, user interaction is minimized which is beneficial, for example, for teaching purposes. However, the drawback of this increased user-friendliness is less flexibility with regard to future efforts that involve the further development and application of BEPS as a research tool.

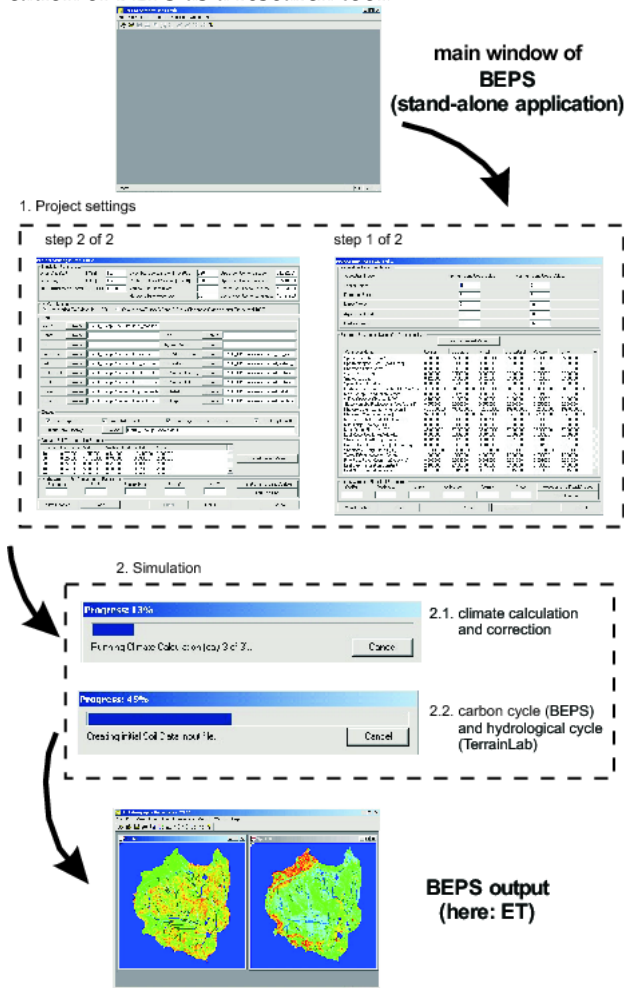


Figure 1: Application of the current version of BEPS containing a GUI on Microsoft's Windows platform.

My doctoral research involves the further development of BEPS towards a distributed, process-oriented ecosystem model of general applicability to individual peatlands of contrasting climatic, topo-

graphic, and (hydro) geologic settings in northern ecozones, able to reliably simulate the relevant hydrological and carbon cycle processes at the (sub-) watershed scale (1 - 100 km²).

In a first preparatory step I qualitatively evaluated the potential technical and scientific benefits of the application of BEPS in a GRASS GIS framework (v. 5.3.0) in combination with the mathematical and statistical programming language R (v. 1.9.1) on a Linux platform (SuSe[®] v. 9.0). A brief introduction to the main modeling hypotheses underlying BEPS, a description of the technical efforts undertaken for the integration of BEPS into GRASS GIS, and a discussion of the potential benefits of the integration are provided in the following sections.

The Boreal Ecosystem Productivity Simulator

BEPS was originally developed to assist in natural resource management and to simulate the carbon budget over the Canadian landmass. The most significant features of BEPS include modeling hypotheses related to the calculation of net primary productivity (NPP) and evapotranspiration (ET) in boreal and (sub-) arctic ecozones at a daily time-step.

NPP is the difference between gross primary productivity (GPP) and autotrophic respiration. In BEPS, GPP is calculated for overstory (Liu et al. , 1999) using a canopy-level photosynthesis model based on an instantaneous leaf-level photosynthesis model (Farquhar et al. , 1980). The upscaling of photosynthesis from leaf to canopy and from an instance of time to a day is accomplished with a spatial and temporal scaling scheme (Chen et al. , 1999). Autotrophic respiration for overstory is calculated as the sum of maintenance and growth respiration. Maintenance respiration is a product of biomass; growth respiration is calculated as a fraction of GPP (Liu et al. , 1999).

ET is calculated for several common overstory, understory, and soil components including snow sublimation from plants and soil. Transpiration from overstory and understory and evaporation from soil are calculated using the Penman-Monteith equation (Monteith , 1965). The upscaling of transpiration from leaf to canopy and from an instance of time to a day is accomplished by replacing stomatal resistance with canopy resistance using the same sunlit and shaded leaf separation approach as for NPP. Evaporation and sublimation from plants are both calculated from intercepted precipitation and the available energy for conversion of liquid or solid water to water vapour. Intercepted precipitation is assumed to be proportional to LAI, constrained by precipita-

tion, either rain or snow. Sublimation from snow is simply calculated based on available energy for conversion of solid water to water vapour. The soil water balance, and therefore the soil moisture content used for the calculation of the leaf water potential (Running et al. , 1988) required for the estimation of stomatal conductance (Jarvis , 1976), is calculated using a simple "bucket" model (Liu et al. , 1997), only considering vertical fluxes of water. In order to include topographic effects on the calculation of the soil water balance and the spatial variability of soil moisture content, the Distributed Hydrology Soil Vegetation Model (DHSVM) developed by Wigmosta et al. (1994) was adopted with several modifications and integrated in BEPS.

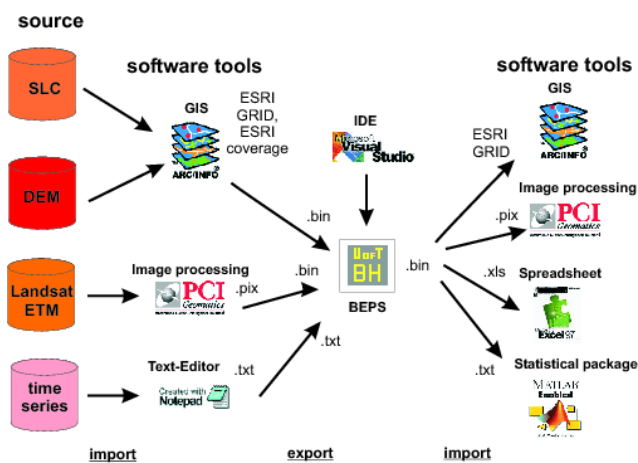


Figure 2: Workflow of the current version of BEPS as a stand-alone application on Microsoft's Windows platform.

BEPS operates with geographically prescribed, non-dynamic input data sets as square grid rasters and requires information on land cover type and leaf area index (LAI), both derived from satellite remote sensing images. Furthermore, spatially explicit input data of available soil water holding capacity, soil texture, initial soil water content, initial snow depth, and soil depth in addition to slope, aspect, and a watershed boundary derived from a digital elevation model (DEM) are required. Spatially explicit daily climatological input data sets (surface radiation, precipitation, and maximum, minimum, and dew point temperature) are constructed from measured time series data and corrected for temperature (slope and aspect) and surface radiation (elevation) before BEPS is run using the climate calculation and correction module.

Integration of BEPS and GRASS GIS in combination with R

The workflow for the application of the current version of BEPS on Microsoft's Windows platform generally encompasses several data conversions between various formats and applications (fig. 2)¹.

For example, in (Liu et al. , 1997, 1999, 2002) information on available soil water holding capacity was obtained from processing ESRI coverages from the Soil Landscapes of Canada (SLC) database² using ESRI's ArcInfo[®] workstation. Generally, satellite remote sensing images (e.g., Landsat TM/ETM+) used for land cover classification and LAI mapping are subjected to several corrections such as geometric, radiometric, and atmospheric, and require the application of a remote sensing image processing software package such as PCI Geomatica[®]. However, regardless of the software package used for the preparation of the respective data set, for the actual model run, all data sets have to be converted to binary files.

The binary model outputs obtained from BEPS can be displayed for a first visual inspection using the basic spatial data handling capabilities provided by the GUI of the current version (fig. 1). Further analysis and validation of the model outputs as well as subsequent map production requires the application of GIS, remote sensing image processing, and statistical packages (e.g., Matlab) (fig. 2).

In order to make use of the square grid raster, image processing, and graphic production capabilities of GRASS GIS in combination with the analytical capabilities of R (Bivand , 2000) for the modeling purposes with BEPS, the BEPS source code was "tightly coupled" (Brimicombe , 2003) with GRASS GIS. For this purpose, the two new commands

- r.climatecalc
- r.bepsterrain

for the climate calculation and correction module and the actual BEPS model, respectively, were created (fig. 3). After typing any of the two commands at the shell prompt, the user is asked to specify a file for certain simulation parameters such as day of the year for the start and the end of the simulation, corner coordinates of the square grid raster, and vertical and horizontal resolution, and the required spatially explicit input data sets, all of which are accessed as GRASS GIS raster files from the database in the specified mapset.

Over the years, the original version of BEPS has undergone continuous refinement and further development by different scientists. As a result, the current

¹This figure includes a word that is or is asserted to be a proprietary term or trade mark. Its inclusion does not imply it has acquired for legal purposes a non-proprietary or general significance, nor is any other judgment implied concerning its legal status.

²<http://sis.agr.gc.ca/cansis/nsdb/sic/intro.html>

implementation of BEPS' modeling hypotheses including utility functions such as data I/O consists of about 8500 lines of just sparsely documented and commented source code. A detailed analysis of the source code revealed that almost all data input/output (I/O) is accomplished through standard ANSI C library functions from the main() functions of the climate calculation and correction module and the actual simulation code, respectively. However, some of the input data sets used by BEPS during execution are accessed by the respective function from different modules when needed, which at the beginning lead to difficulties in tracing the data flow.

After centralizing all data I/O in the respective main() function, the programming effort for the integration of BEPS and GRASS GIS was minimal. The integration was accomplished by following the approach pursued by *r.example* which is available from the GRASS GIS CVS repository.

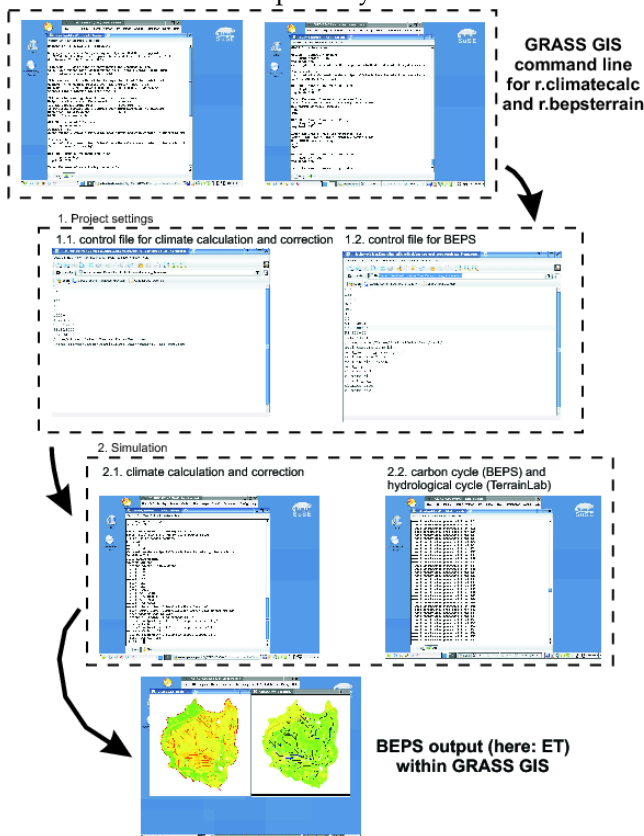


Figure 3: Application of BEPS integrated in GRASS GIS on a Linux platform.

Discussion and conclusions

The application of GRASS GIS as an integrated platform for the modeling purposes with BEPS in combination with R supersedes the application of multiple software packages and the implied conversion from proprietary data formats to binary files and back

(fig. 4). Furthermore, using Open Source software in the model development process allows the quick and straightforward adaptation of modeling source code as was demonstrated by simply adopting the well documented approach of *r.example*. Thereby, as demonstrated with the tight integration of BEPS and GRASS GIS, the full range of capabilities provided by GRASS GIS and R can be easily utilized by existing legacy modeling source code. As a result, GRASS GIS can be considered as the ideal computational platform for the modeling purposes with BEPS and their integrated use is of great technical and computational benefit. However, the current state-of-the-art for the integrated use of GIS and process-oriented models in general, regardless of the level of integration (loosely coupled, tightly coupled, and embedded after (Brimicombe, 2003)), is still purely a technical solution as to how both technologies "can share the same data rather than being integrated in terms of achieving compatible views of the world" (see Brimicombe, 2003, p. 170).

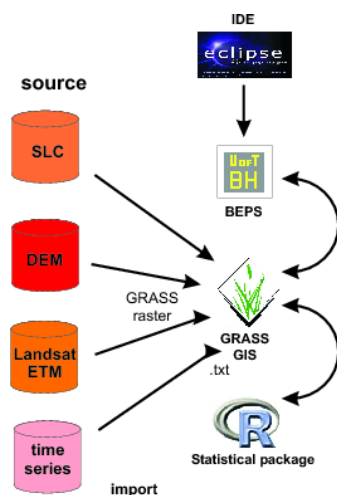


Figure 4: Workflow of BEPS integrated in GRASS GIS in combination with R on a Linux platform.

The reason for this deficiency lies in the fundamentally different abstraction of the world, represented by the underlying conceptual data models. Therefore, none of the currently applied ways of integrating GIS and process-oriented models has the capability to be considered as an enhanced means to provide additional insights into the functioning of complex environmental systems such as peatlands other than the insights gained from the application of the model itself.

As a result, for the purposes of my doctoral research, GRASS GIS is going to be of great importance from a technical and computational point of view, but is completely irrelevant for the achievement of my scientific goals.

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Bibliography

- R. S. Bivand (2000) Using the R statistical data analysis language on GRASS 5.0 GIS database files. *Computers & Geosciences* 26: 1043-1052.
- A. Brimicombe (2003) *GIS, environmental modelling and engineering*. New York, USA: Taylor & Francis
- J. M. Chen, J. Liu, J. Chilar, M.L. Goulden (1999) Daily canopy photosynthesis model through temporal and spatial scaling for remote sensing applications. *Ecological Modelling* 124: 99-119.
- G. D. Farquhar, S. von Caemmerer, J.A. Berry (1980) A biochemical model of photosynthetic CO₂ assimilation in leaves of C₃ species. *Planta* 149: 78-90.
- P. G. Jarvis (1976) The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Philosophical Transactions Of The Royal Society Of London*: 593-610.
- J. Liu, J. M. Chen, J. Chilar, W. M. Park (1997) A process-based Boreal Ecosystem Productivity Simulator using remote sensing inputs. *Remote Sensing of Environment* 62: 158-175.
- J. Liu, J. M. Chen, J. Chilar, W. Chen (1999) Net primary productivity distribution in the BOREAS region from a process model using satellite and surface data. *Journal of Geophysical Research-Atmospheres* 104: 27735-27754.
- J. Liu, J. M. Chen, J. Chilar, W. Chen (2002) Net primary productivity mapped for Canada at 1-km resolution. *Global Ecology and Biogeography* 11: 115-129.
- J. L. Monteith (1965) Evaporation and environment. in *Proceedings of the 19th Symposium of the Society for Experimental Biology* New York, USA: Cambridge University Press.
- S. W. Running, J. C. Coughlan (1988) A general model of forest ecosystem processes for regional applications. 1. Hydrologic balance, canopy gas-exchange and primary production processes. *Ecological Modelling* 42: 125-154.
- M. S. Wigmosta, L. W. Vail, D. P. Lettenmaier (1994) A distributed hydrology-vegetation model for complex terrain. *Water Resources Research* 30: 1665-1679.

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r.roughness – a new tool for morphometric analysis in GRASS

by Carlos Henrique Grohmann

Introduction

This article briefly describes `r.roughness`, a shell script written to calculate the surface roughness of raster surfaces. The method is based on Hobson (1972), where roughness is defined as the ratio between surface and plan area of square cells. This script will create square sub-regions with size defined by the user; in each sub-region, the real and planar areas will be calculated by `r.surf.area`, and the results (points at the centre of sub-regions) will be interpolated with `v.surf.rst`. The user also can set the tension and smooth parameters of interpolation.

Surface Roughness

Surface roughness (or topographical roughness) was first introduced as a morphometric parameter by

Stone and Dugundji (1965) and Hobson (1967, 1972). To Hobson (1972), one possible way to calculate it is the ratio between surface (real) area and flat (plan) area of square cells; in this approach, flat surfaces would present values close to 1, whilst in irregular ones the ratio shows a curvilinear relationship which asymptotically approaches infinity as the real areas increases.

Day (1979) describes surface roughness as the expression of non-systematic variability of the topographic surface, and used the dispersion of vector normals to surface plans as a roughness indicator to discriminate tropical karst stiles.

Ferrari et al. (1998) argue that surfaces with distinct characteristics can present the same roughness value, due the existence of interactions between the number and magnitude of terrain irregularities. Grohmann (2004), considers this method useful for morphological characterisation since it is mainly related with the shape of land-forms and not its elevation; thus, tectonically tilted areas have their expression shown, while it could be masked in a hypsometric map, as consequence of altimetric variations.