**Supplementary material: appendices A and B**

**Appendix A: Gras-Sim model description**

Gras-Sim allows to simulate the daily biomass dynamics in a permanent grassland. It is based essentially on three existing models: ModVege (Jouven et al., 2006), CATIMO (Bonesmo and Bélanger, 2002) and MoSt GG model (Ruelle et al., 2018).

1. **Biomass dynamics**

Gras-Sim presents the structure of the biomass in 4 categories as it is the case in ModVege: biomass green vegetative (BMGV, kg DM ha-1), biomass green reproductive (BMGR, kg DM ha-1), biomass dead vegetative (BMDV, kg DM ha-1) and biomass dead reproductive (BMDR, kg DM ha-1). The vegetative biomass is composed of leaves and sheath and the reproductive biomass of flowers and stems.

* 1. **Potential growth**

(kg DM ha-1) depends on the incident photosynthetically active radiation (PARi, MJ m-2), the maximum efficiency of use of this radiation by the plant (, g DM MJ-1) and the leaf area index ():

|  |  |  |
| --- | --- | --- |
|  |  | (1) |

Where PARi is the model input data measured in the field by a weather station. varies according to the PFT. The values of this parameter used in Gras-Sim are given in appendix B (Table B.1). LAI is a function of specific leaf area (SLA, m2 g-1), the percentage of green laminae (%LAM) whish values are also given in appendix B (Table B.1) and the vegetative part of the green biomass (BMGV kg DM ha-1). It is calculated according to the following equation:

|  |  |  |
| --- | --- | --- |
|  |  | (2) |

* 1. **Seasonal effect**

SEA is an empirical threshold function that describes the seasonal growth of shoot due to storage and mobilization of reserves (Jouven et al., 2006). It is therefore related to the accumulated degrees days**.**

|  |  |  |
| --- | --- | --- |
|  |  | (3) |

Where ST (°C) is the sum of daily positive temperatures from January 1. and are the minimum and maximum values of SEA, respectively. These two threshold values are indicated in appendix B (Table B.1)**.**

* 1. **Growth Reduction Factors**

holds environmental limitations to the potential growth, ranging between 0, no growth, and 1, no limitation to the growth. It combines four functions (Eq. (4)), related to plant nitrogen nutrition status (), adapted from the CATIMO model, temperature , photosynthetically active radiation () and soil water (). All these functions vary between 0 and 1:

|  |  |  |
| --- | --- | --- |
|  |  | (4) |

**N factor**

depends essentially on the nitrogen nutrition status of the plant expressed by the relative N concentration () which is the ratio of the actual N concentration (g N 100g-1 DM) to the critical N concentration ():

|  |  |  |
| --- | --- | --- |
|  |  | (5) |

Where 𝑁𝑐𝑟𝑖𝑡 (%) is calculated on the basis of the exportable biomass, i.e. the biomass above 5 cm (, kg DM ha-1). It is the same for the plant functional types (PFTs) A and B. 𝑁𝑐𝑟𝑖𝑡 follows the critical N dilution curve described by Lemaire et al., (1984):

|  |  |  |
| --- | --- | --- |
|  |  | (6) |

is also calculated on the basis of the exportable biomass. If is zero, is equal to 𝑁𝑐𝑟𝑖𝑡. Therefore, we consider any effect of potential nitrogen stress on biomass production to be null. When is less than one ton, we assume that the N concentration (, , kg N kg MD-1) in the green parts (,is at the critical concentration, which is not the case for the N concentration (, , kg N kg MD-1) in the dead parts (,. The value the relative N concentration () in the lower parts, below 5 cm, was set at 0.4.

|  |  |  |
| --- | --- | --- |
|  |  | (7) |

The N concentration in the different compartments (, , ) is calculated at the beginning of the simulation by taking the ratio between the N quantity (NQ, kg N ha-1) and the biomass:

|  |  |  |
| --- | --- | --- |
|  |  | (8) |
|  |  | (9) |
|  |  | (10) |
|  |  | (11) |

The N quantity in the different compartments ( is given by equations (35), (36), (37) and (38).

is finally calculated according to the following equation:

|  |  |  |
| --- | --- | --- |
|  |  | (12) |

**PARi factor**

presented in LINGRA (Schapendonk et al., 1998) and reported in ModVege reflects the reduction of the RUE when the light intensity is higher than 5 MJ m-2.

|  |  |  |
| --- | --- | --- |
|  |  | (13) |

Where is in MJ m-2.

**Temperature factor**

comes also from the LINGRA model and reported in ModVege. It describes the activation of photosynthesis when the average temperature of the 10 previous days is higher than the threshold temperature T0 and stimulation by the daily average temperature until the optimal temperature range between T1 and T2.

|  |  |  |
| --- | --- | --- |
|  |  | (14) |

Where Temp is the daily mean temperature expressed in °C. The values of the parameters T0, T1, T2, and are given in appendix B (Table B.1).

**Water factor**

Like nitrogen, soil water availability impacts plant growth. This influence results in a decrease in growth when the water stress (W) increases. The water stress function () is from McCall and Bishop-Hurley, (2003) and has been included in ModVege.

|  |  |  |
| --- | --- | --- |
|  |  | (15) |

where water (mm) is soil water content, (mm) is water at wilting point and (mm) is water at field capacity. The calculation of these different variables is given in the section on soil water.

|  |  |  |
| --- | --- | --- |
|  |  | (16) |

For 0 < PET ≤ 3.81

|  |  |  |
| --- | --- | --- |
|  |  | (17) |

For 3.81< PET ≤ 6.35

|  |  |  |
| --- | --- | --- |
|  |  | (18) |

For PET > 6.35

|  |  |  |
| --- | --- | --- |
|  |  | (19) |

PET (mm) is the potential evapotranspiration measured in the field by a weather station.

* 1. **Growth**

Daily plant growth (kg DM ha-1) is driven by potential growth (PGRO) obtained under optimum conditions and limited by both environmental factors (ENV) and seasonal effect (SEA) of the shoot growth, conditioned by the storage and mobilization of reserves (Jouven et al., 2006)

|  |  |  |
| --- | --- | --- |
|  |  | (20) |

A reproductive function (), which varies between 0 and 1, allows the distribution of the total growth according to the vegetative (, kg DM ha-1) and reproductive (, kg DM ha-1) compartments:

|  |  |  |
| --- | --- | --- |
|  |  | (21) |
|  |  | (22) |

* 1. **Plant Senescence and abscission**

The plant enters senescence () and then abscission () after its growth phase. The proportion of green biomass (, kg DM ha-1), the daily temperature (Temp), the basic senescence rate () and the age of the green biomass () are the factors that influence the senescence function. The abscission will depend on the senescing biomass (, kg DM ha-1) the basic abscission rate () and the age of the dead biomass () in addition to the daily temperature (Jouven et al., 2006). The following equations describing senescence and abscission are the same for the vegetative and reproductive compartments:

|  |  |  |
| --- | --- | --- |
|  |  | (23) |
|  |  | (24) |

Where (°C) is the minimum temperature for growth. The values of , and are presented in appendix B (Table B.1). The age function represents the effect of biomass age on secnessence and abscission. The age of the biomass varies between green () and dead () compartments( Jouven et al., 2006). The equations are the same for the vegetative and reproductive compartments:

|  |  |  |
| --- | --- | --- |
|  |  | (25) |
|  |  | (26) |

is the rate of biomass losses by respiration during the senescence which value is presented in appendix B (Table B.1). The effect of age of vegetative compartments () on senescence and abscission is not the same as that of reproductive compartments () (Jouven et al., 2006):

|  |  |  |
| --- | --- | --- |
|  |  | (27) |
|  |  | (28) |
|  |  | (29) |
|  |  | (30) |

Where , °C d) is the leaf life span. (°C) and (°C) are the sum of temperatures from January 1 to the beginning and end of the reproductive period, respectively. The values of these different parameters are given in Appendix B (Table B.1).

* 1. **Biomass balance**

The Daily Biomass variation of the green compartments (BMG, kg DM ha-1) is the difference between the growth (GRO, kg DM ha-1) and the biomass lost by senescence (, kg DM ha-1) and defoliation (EXPBM, kg DM ha-1). The equations are the same for the vegetative and reproductive compartments:

|  |  |  |
| --- | --- | --- |
|  |  | (31) |

The pool of dead biomass (BMD, kg DM ha-1) is increased daily by the amount of biomass entering senescence and decreased by the amount lost to abscission (kg DM ha-1). The equations are the same for the vegetative and reproductive compartments:

|  |  |  |
| --- | --- | --- |
|  |  | (32) |

Where is the rate of biomass losses by respiration during the senescence. It is distributed in vegetative () and reproductive () compartments. The values of these two parameters are provided in Appendix B (Table B.1).

1. **Organic matter digestibility**

The organic matter digestibility in green vegetative (, g g-1) and reproductive (, g g-1) compartments evolves with the age of the plant. The maximum digestibility (, , g g-1), a theoretical value at zero age, will progressively decrease to reach its minimum (, , g g-1) value at the maximum age, which is the leaf life span () for the green vegetative (GV) compartment and the duration of the reproductive period (, °C d) for the green reproductive (GR) compartment (Jouven et al., 2006):

|  |  |  |
| --- | --- | --- |
|  |  | (33) |
|  |  | (34) |

Where (°C d) is the age of the biomass in the GV compartment and (°C d), the age of the biomass in the GR compartment. The values of the parameters , , , , and are presented in Appendix B (Table B.1). The digestibility of the dead plant material (OMDDV, OMDDR) is constant and given in Appendix B (Table B.1).

1. **N balance in the plant**

As for the biomass, the N flux at the pasture scale is the combination of the flux in each of the compartments: (kg N ha-1), the N content of the green compartments and (kg N ha-1) the N content of the dead compartments. The daily variation of the plant N content corresponds to the difference between the absorbed soil nitrogen (, kg N ha-1) that remains in the above-ground biomass (Bonesmo and Bélanger, 2002) and nitrogen that is lost through senescence (, kg DM ha-1) for green compartment or abscission (, kg DM ha-1) for dead parts. These variations are described by the following equations:

|  |  |  |
| --- | --- | --- |
|  |  | (35) |
|  |  | (36) |
|  |  | (37) |
|  |  | (38) |

Where and represent the rates of biomass loss by respiration during senescence for the GV and GR compartments, respectively (Table B.1). is the N content in the dead material that goes to the soil by abscission. It is fixed at 8 g N kg-1 DM (Ruelle et al., 2018) (Table B.3). The fraction of absorbed N () that remains in the aboveground biomass, increases when the N status of the plant increases. It is adapted from the CATIMO model for the PFTs A and B:

|  |  |  |
| --- | --- | --- |
|  |  | (39) |

Where is the maximum value of , given in appendix B (Table B.3).

1. **Soil water and nitrogen dynamics**
   1. **Wilting point (mm)**

|  |  |  |
| --- | --- | --- |
|  |  | (40) |

Clay and OM are respectively the proportion (%) of soil clay and organic matter.

* 1. **Field capacity (mm)**

|  |  |  |
| --- | --- | --- |
|  |  | (41) |

Sand is the sand content (%) of the soil.

* 1. **Saturation (mm)**

|  |  |  |
| --- | --- | --- |
|  |  | (42) |

* 1. **Soil Water balance**

On a given day the soil water (, mm) balance is calculated as the sum of the rainfall (, mm) and the surplus of water from the previous day(mm), if any, from which the water lost by evapotranspiration (, mm) and leaching ( mm) is removed:

|  |  |  |
| --- | --- | --- |
|  |  | (43) |

If the soil water content is above the saturation point (, mm) , 20% of the surplus water () is kept on the plot and is be added to the water reserve of the next day (Ruelle et al., 2018). Where:

|  |  |  |
| --- | --- | --- |
|  |  | (44) |
|  |  | (45) |

* 1. **NH3 volatilization factor**

is a special factor to account for the amount of N lost to volatilization when applying N in organic form. Its value varies depending on whether the application conditions are good or not (Ruelle et al., 2018):

|  |  |  |
| --- | --- | --- |
|  |  | (46) |

* 1. **N in the abscission material**

The proportion of N ( ) in the material in abscission ( and, kg DM ha-1) was set at 8 g N kg-1 DM (Ruelle et al., 2018). The N entering the soil through the dead material is calculated using the following equation:

|  |  |  |
| --- | --- | --- |
|  |  | (47) |

* 1. **N leached**

Soil mineral N (, kg N ha-1) lost through leaching is calculated as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (48) |

* 1. **N from rain**

The mineral N (, kg N ha-1) added to the soil by precipitation (, mm) is determined by the following equation (Ruelle et al., 2018):

|  |  |  |
| --- | --- | --- |
|  |  | (49) |

* 1. **Mineralization and immobilization**

Nitrogen mineralization and immobilization depend on the variation ( of soil water and a temperature function ( (Ruelle et al., 2018):

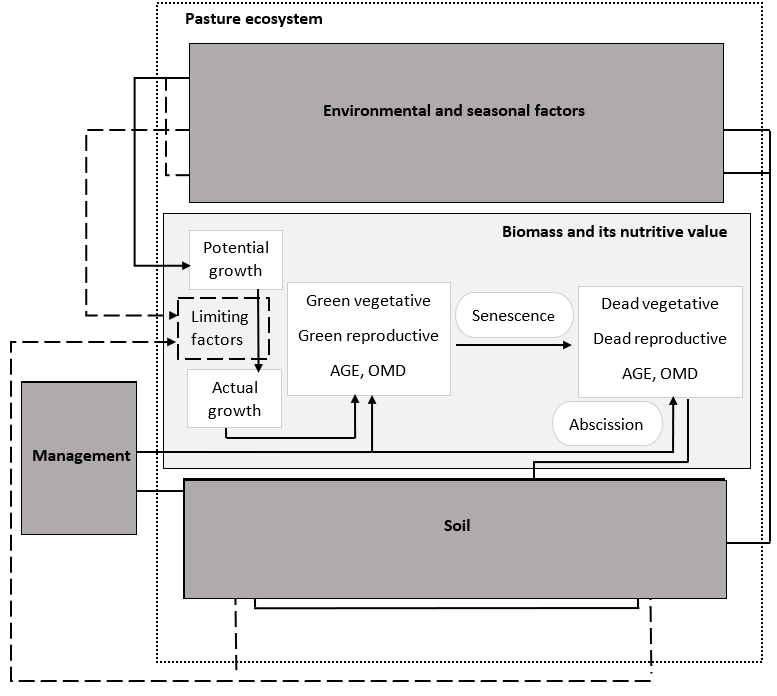
|  |  |  |
| --- | --- | --- |
|  |  | (50) |
|  |  | (51) |

Where:

|  |  |  |
| --- | --- | --- |
|  |  | (52) |
|  |  | (53) |
|  |  | (54) |
|  |  | (55) |

is the reference temperature for soil activity. Its value is given in appendix B (Table B.3).

**Appendix B: Gras-Sim sub-model diagrams and parameter values**.



**Fig. 1** Flow diagram of the biomass production and nutritional value submodel for functional types A and B. Rectangular boxes represent state variables and driving variables. Processes are represented by the rounded boxes on the sides. Solid arrows show direct and feedback effects of different variables, and dotted arrows show limiting effects on growth.

Tableau

**Table 1**

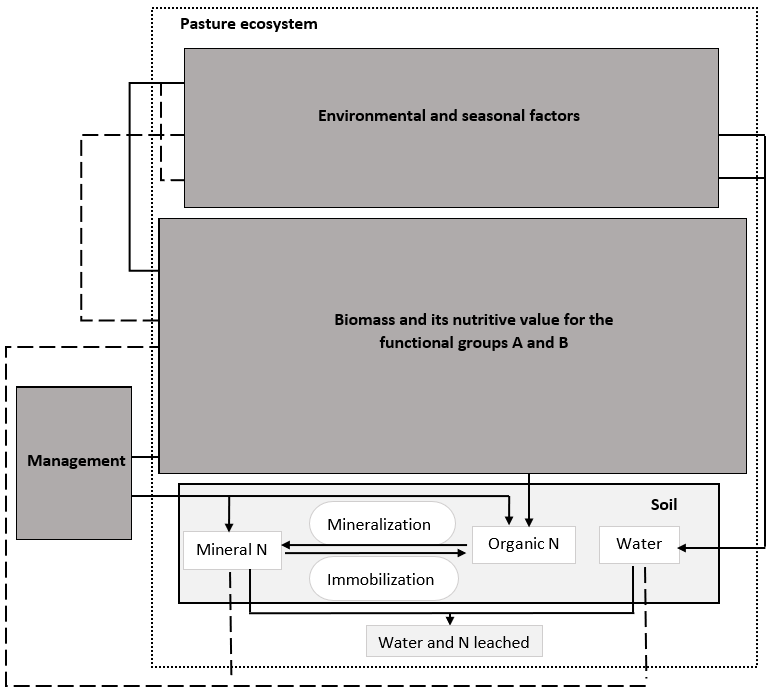
Gras-Sim model: biomass dynamics parameters

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameters | Description (unit) | PFT A | PFT B | Reference |
| ST1 | Sum of temperature from 1 January to the beginning of the reproductive period (°C d) | 500 | 600 | Cruz et al., 2010 |
| ST2 | Sum of temperature from 1 January to the end of the reproductive period (°C d) | 900 | 1200 | Cruz et al., 2010 |
| SLA | Specific leaf area (m2 g-1) | 0.023 | 0.020 | Cruz et al., 2010 |
| LLS | Leaf lifespan (°C d) | 800 | 1000 | Cruz et al., 2010 |
| minSEA | Minimum seasonal effect | 0.8 | 0.8 | Adapted from Jouven et al., 2006 |
| maxSEA | Maximum seasonal effect | 1 | 1 | Adapted from Jouven et al., 2006 |
| maxOMDGV | Maximum organic matter digestibility of green vegetative | 0.9 | 0.9 | Jouven et al., 2006 |
| maxOMDGR | Maximum organic matter digestibility of green reproductive | 0.9 | 0.9 | Jouven et al., 2006 |
| minOMDGV | Minimum organic matter digestibility of green vegetative | 0.75 | 0.6 | Jouven et al., 2006 |
| minOMDGR | Minimum organic matter digestibility of green reproductive | 0.65 | 0.45 | Jouven et al., 2006 |
| BDGV | Bulk density of green vegetative (g DM m-3) | 800 | 850 | Adapted from Jouven et al., 2006 |
| BDGR | Bulk density of green reproductive (g DM m-3) | 300 | 300 | Adapted from Jouven et al., 2006 |
| BDDV | Bulk density of dead vegetative (g DM m-3) | 500 | 550 | Adapted from Jouven et al., 2006 |
| BDDR | Bulk density of dead reproductive (g DM m-3) | 150 | 150 | Adapted from Jouven et al., 2006 |
| RUEmax | Maximum radiation use efficiency (g DM MJ-1) | 2.6 | 2.9 | Cristiano et al., 2015 |
| %LAM | Percentage of laminae | 0.68 | 0.68 | Jouven et al., 2006 |
| OMDDV | Organic matter digestibility of dead vegetative | 0.45 | 0.45 | Jouven et al., 2006 |
| OMDDR | Organic matter digestibility of dead reproductive | 0.40 | 0.40 | Jouven et al., 2006 |
| T0 | Minimum growth air temperature (°C) | 4 | 4 | Jouven et al., 2006 |
| T1 | Air temperature at which growth plateau is reached (°C) | 10 | 10 | Jouven et al., 2006 |
| T2 | Air temperature at which growth starts decreasing (°C) | 20 | 20 | Jouven et al., 2006 |
| Tlimit | Air temperature at which growth ends (°C) | 25 | 25 | Jouven et al., 2006 |
| STmin | Minimum sum of temperature for growth (°C) | 200 | 200 | Jouven et al., 2006 |
| σGV | Rate of green vegetative biomass losses with respiration | 0.40 | 0.40 | Jouven et al., 2006 |
| σGR | Rate of green reproductive biomass losses with respiration | 0.20 | 0.20 | Jouven et al., 2006 |
| KlDV | Basic abscission rate for dead vegetative | 0.0001 | 0.0001 | Ruelle et al., 2018 |
| KlDR | Basic abscission rate for dead reproductive | 0.0005 | 0.0005 | Ruelle et al., 2018 |
| KGV | Basic senescence rate for green vegetative | 0.0002 | 0.0002 | Ruelle et al., 2018 |
| KGR | Basic senescence rate for green reproductive | 0.0001 | 0.0001 | Ruelle et al., 2018 |

**Table 2**

Gras-Sim model: Kc values for grassland (adapted from Liu et al., 2017)

|  |  |
| --- | --- |
| Month | Kc |
| January | 0.11 |
| February | 0.15 |
| March | 0.24 |
| April | 0.4 |
| May | 0.49 |
| June | 0.6 |
| July | 0.6 |
| August | 0.47 |
| September | 0.37 |
| October | 0.36 |
| November | 0.23 |
| December | 0.15 |



**Fig. 2** Flow diagram of the soil water and nitrogen dynamics submodel. Rectangular boxes represent state variables and driving variables. Processes are represented by the rounded boxes on the sides. Solid arrows show direct and feedback effects of different variables, and dotted arrows show limiting effects on growth.

Table

**Table 3**

Gras-Sim model: plant and soil N parameters

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameters | Description (unit) | PFT A | PFT B | Reference |
| FNHmax | Maximum value of N fraction absorbed that remains in the above-ground biomass | 0.8 | 0.8 | Bonesmo and Bélanger, 2002 |
|  | Proportion of N in the abscission material (g N kg-1 DM) | 8 | 8 | Ruelle et al., 2018 |
| Tref | Reference temperature for soil activity (°C) | 15 | 15 | Ruelle et al., 2018 |
|  | Maximum plant %N at 1 t shoot biomass ha-1 | 6.145 | 5.56 | Lemaire and Denoix, 1987 & Marino et al., 2004 |
|  | Maximum pattern of decrease of %N during increased shoot biomass | 0.418 | 0.44 | Lemaire and Denoix, 1987 & Marino et al., 2004 |
|  | Soil N content for maximum N availability (kg N ha-1) | 250 | 250 | Adapted from Bonesmo and Bélanger, 2002 |
| FNAmax | Maximum fraction of available soil N | 0.07 | 0.07 | Adapted from Bonesmo and Bélanger, 2002 |

**References**

Bonesmo, H., Bélanger, G., 2002. Timothy yield and nutritive value by the CATIMO model: I. Growth and nitrogen. Agron. J. 94, 337–345.

Cristiano, P.M., Posse, G., Di Bella, C.M., 2015. Total and aboveground radiation use efficiency in C 3 and C 4 grass species influenced by nitrogen and water availability. Grassl. Sci. 61, 131–141.

Cruz, P., Theau, J.P., Lecloux, E., Jouany, C., Duru, M., 2010. Typologie fonctionnelle de graminées fourragères pérennes: une classification multitraits 9.

Jouven, M., Carrere, P., Baumont, R., 2006. Model predicting dynamics of biomass, structure and digestibility of herbage in managed permanent pastures. 1. Model description. Grass Forage Sci. 61, 112–124.

Lemaire, G., Denoix, A., 1987. Croissance estivale en matiere seche de peuplements de fetuque elevee (Festuca arundinacea Schreb.) et de dactyle (Dactylis glomerata L.) dans l’Ouest de la France. I. Etude en conditions de nutrition azotee et d’alimentation hydrique non limitantes. Agron. 6 7 373-380 1987.

Lemaire, G., Salette, J., Sigogne, M., Terrasson, J.-P., 1984. Relation entre dynamique de croissance et dynamique de prélèvement d’azote pour un peuplement de graminées fourragères. I.--Etude de l’effet du milieu. Agronomie 4, 423–430.

Marino, M.A., Mazzanti, A., Assuero, S.G., Gastal, F., Echeverría, H.E., Andrade, F., 2004. Nitrogen Dilution Curves and Nitrogen Use Efficiency During Winter–Spring Growth of Annual Ryegrass. Agron. J. 96, 1. https://doi.org/10.2134/agronj2004.0601

McCall, D.G., Bishop-Hurley, G.J., 2003. A pasture growth model for use in a whole-farm dairy production model. Agric. Syst. 76, 1183–1205. https://doi.org/10.1016/S0308-521X(02)00104-X

Ruelle, E., Hennessy, D., Delaby, L., 2018. Development of the Moorepark St Gilles grass growth model (MoSt GG model): A predictive model for grass growth for pasture based systems. Eur. J. Agron. 99, 80–91.

Schapendonk, A.H.C.M., Stol, W., van Kraalingen, D.W.G., Bouman, B.A.M., 1998. LINGRA, a sink/source model to simulate grassland productivity in Europe. Eur. J. Agron. 9, 87–100. https://doi.org/10.1016/S1161-0301(98)00027-6