Forage Harvest Representation in RUSLE2

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ABSTRACT

The Revised Universal Soil Loss Equation (RUSLE and RUSLE2) has long been used by the USDA and others for management planning based on soil erosion and sediment delivery estimates. It has worked well for normal annual agronomic crops but proved to be awkward for forage crops. This is partly because RUSLE and earlier versions of RUSLE2 calculated vegetative residue production only during periods of canopy decline or in response to management operations, resulting in underestimation of residue amounts, with subsequent overestimation of soil erosion from pasture and hay lands. To solve this problem, a new vegetation model was implemented in RUSLE2 to track the growth, death, and characteristics of perennial vegetation. A complementary comprehensive RUSLE2 harvest process developed to interact with the new vegetation growth model was also developed. This harvest process includes an extensive set of options that provide great flexibility in describing perennial vegetation management systems. In this study, the ability of the new growth model and harvest process to dynamically adjust residue creation in response to alternative forage harvest schemes was investigated through comparison with published studies involving bahiagrass (***Paspalum notatum*** Flügge), bermudagrass [***Cynodon dactylon*** (L.) Pers.], and ryegrass (***Lolium perenne*** L.). The new modeling tools make it easier to model haying and grazing scenarios in perennial systems, to create better estimates of the amount and timing of plant residue added by perennial vegetation during its growth, and thus to improve runoff and soil erosion estimates for conservation planning.

Perennial vegetation is often described in terms of net primary productivity (NPP), which refers to gross photosynthesis minus plant respiration per unit ground area (Wiegert and Evans, 1964; Long et al., 1989; Scurlock et al., 2002; Lauenroth et al., 2006). Net primary production is a stand-level vegetation parameter dependent on the changes in above- and belowground plant mass plus any losses that have occurred during the observation period due to death and subsequent decomposition, herbivory, and exudation/volatilization. If exudation of mass to symbiotic or parasitic organisms, volatilization, and insect feeding are ignored, then NPP for the time interval DT can be represented as

$$\mathrm{NPP} = \Delta B + \Delta D + \mathrm{Dc} + H \quad [1]$$

where ΔB is the change is live biomass, ΔD is the change in dead biomass, Dc is decomposition of dead biomass, and H is biomass (living or dead) removed (harvested) as forage. This equation applies to both above- and belowground biomass.

The change in dead biomass, ΔD, is the net of residue additions due to the death of live biomass minus losses of residue mass to decomposition or removal of dead residue as forage, or

$$\Delta D = \mathrm{De} - (\mathrm{Dc} + \mathrm{Hr}) \quad [2]$$

where De is the death of live biomass and Hr is the harvest of standing residue as forage. Substituting Eq. [2] into [1] gives

$$\mathrm{NPP} = \Delta B + \mathrm{De} + \mathrm{Ha} \quad [3]$$

where Ha is live biomass removed as forage and H = Ha + Hr under the assumption that all forage harvested will be either live aboveground biomass or standing dead residue. Equation [3] indicates that NPP across an interval can be calculated as the sum of the change in live biomass plus death plus live biomass harvested as forage. If over an interval (say, perhaps a year) there is no net change in live or dead biomass and no forage harvest, then NPP equals De (death) equals Dc (decomposition). If forage is harvested and NPP remains the same, the larger the harvest, the less NPP will be diverted to residue production and subsequent decomposition and the greater the subsequent erosion.

A vegetation model that incorporates this scheme has been implemented in the Revised Universal Soil Loss Equation, Version 2 (RUSLE2) (Dabney and Yoder, 2012). The new routines are based on the assumption that all vegetation has a defined lifespan, that unharvested aboveground growth dies after its lifespan is reached, and that this biomass is added to a standing residue

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Abbreviations: AU, animal unit; NPP net primary productivity; IVDOM, in vitro digestible organic matter; RUSLE, Revised Universal Soil Loss Equation; RUSLE2, Revised Universal Soil Loss Equation Version 2.

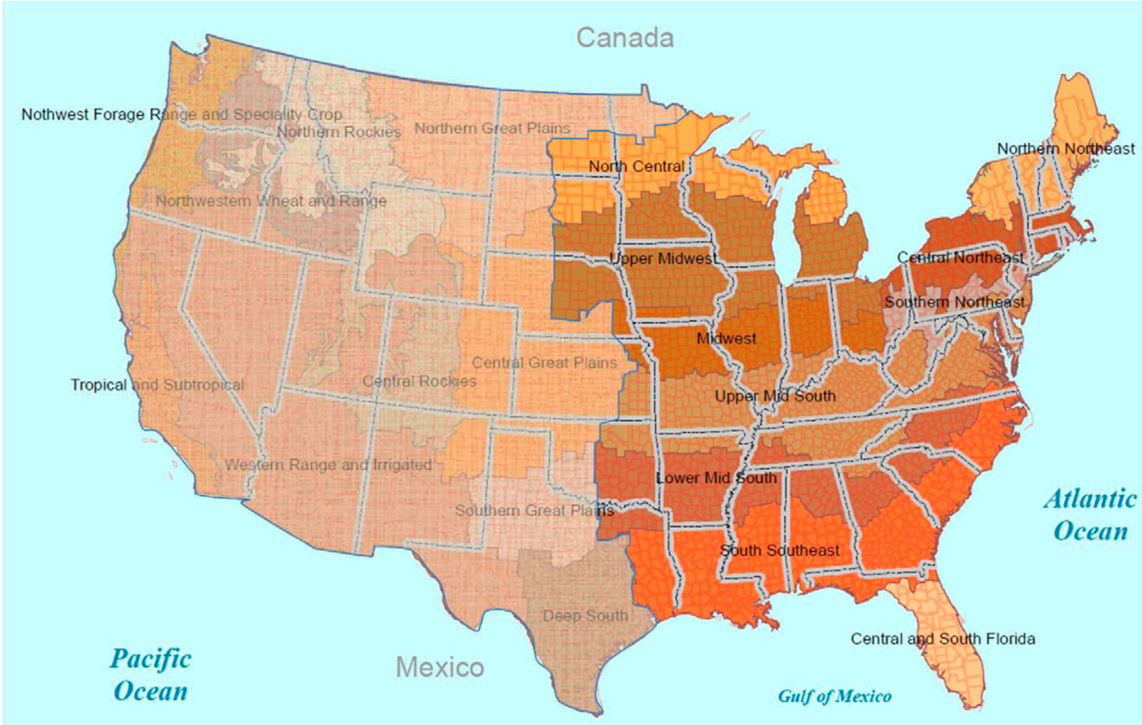

Fig. 1. The NRCS has developed nearly 1000 management descriptions based on combinations of more than 300 vegetation descriptions and 18 pasture and hay harvest operations that make use of the new RUSLE2 vegetation model. These management descriptions are organized into "forage production zones" that currently cover the eastern half of the United States and the Caribbean. The forage database for the western United States has not been populated, and boundaries and names of the proposed western forage production zones have not been verified.

pool. The characteristics of a vegetation assemblage are described in terms of the monthly distribution of total annual potential production under good management, and RUSLE2 determines the effects of alternative management systems on the amount of harvested forage, the amount of above- and belowground residues returned to the soil, and the resulting runoff and soil loss.

During the course of several years, a RUSLE2 Forage Team, comprised of programmers, agronomists, and grazing lands specialists, developed the underlying model and new associated interface tools in an effort to support the creation of management scenarios that take advantage of the abilities of the new vegetation model. Trained specialists identified categories and contingencies necessary to adequately describe haying and grazing management systems. Haying and grazing management details can greatly affect the fate and partitioning of aboveground biomass between forage removal and residue creation, and thus not only the resulting forage harvest but also the estimated runoff and erosion. Here we describe and illustrate the implementation of new forage management and harvest schemes within RUSLE2 as developed by the RUSLE2 Forage Team. Simultaneously with the development of the scientific model and interface tools described here, the NRCS has developed a database to make use of this new technology. Vegetation, harvest operation, and forage management descriptions have so far been organized into "forage production zones" covering the eastern half of the United States (Fig. 1).

RUSLE2 ORGANIZATION

RUSLE2 generally calculates runoff, erosion, and sediment delivery from hillslope profiles, which include information describing the climate, topography, soils, land management, and concentrated flow path properties of a site (Fig. 2). RUSLE2 can also calculate erosion at two higher levels of organization: (i) the worksheet, in which a variety of land management and support practice descriptions can be compared for a single combination of location, soil, and topography; and (ii) the plan, which calculates a weighted average of several different profiles representative of a field or watershed (see USDA-ARS, 2008, Section 5.6).

Land management descriptions in RUSLE2 comprise combinations of field operations and vegetations. Field operations typically describe tillage, planting, and harvest or grazing events that occur on particular dates and that affect the land surface by creating roughness, adding or removing biomass, mixing residues into the soil, or starting or ending vegetation growth. Vegetation descriptions specify temporal growth patterns, the canopy cover, height, and shape, harvest biomass relationships, hydraulic roughness properties, and associated residue characteristics for a single species or a mixture of species. Operations are made up of combinations of one or more RUSLE2 "processes" (Table 1). These processes often include a number of associated parameters that can be given default values and stored as named operations, which are then used to develop land management descriptions. When used in a management, default process properties can be overwritten by the user, and the resulting management values may be used in a profile to estimate land management effects on runoff and erosion. The first 10 processes listed in Table 1 are discussed in detail in USDA-ARS (2008).

Perennial Biomass and Current Standing Residue Removal Process

A new process (Process 11 in Table 1) was added to RUSLE2 to manage the new perennial vegetation model described by Dabney and Yoder (2012). The options and parameters for this

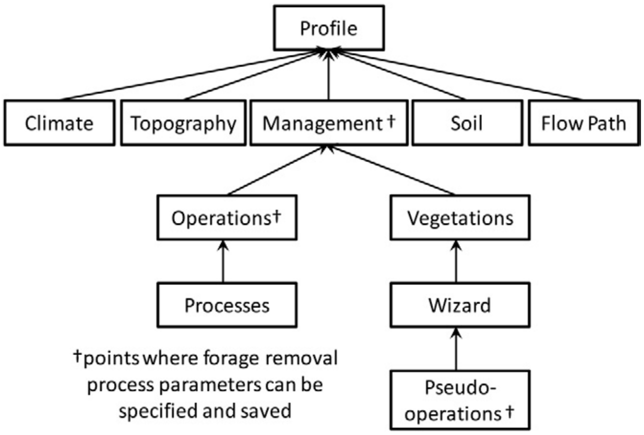

Fig. 2. Management information related to the new forage model may be specified in three places: (i) pseudo-operations within the vegetation wizard that are used to test how a vegetation under development will respond to management, (ii) operations, where default process parameter values can be set and saved with a descriptive name, and (iii) actual management, where default values from operation and vegetation descriptions may be overwritten and that are used by RUSLE2 to compute runoff, erosion, sediment delivery, and forage harvest at the profile level.

process when used in a land management description are listed in Table 2. The first option that must be specified is the "method of forage removal." The RUSLE2 Forage Team developed the 12 forage removal method choices shown in Table 3, along with the other process parameters that must be specified depending on the selected forage removal method.

Seven of the forage removal methods are "season-long" methods and require specification of a grazing season length. These season-long methods allow the user to set conditions that trigger a harvest event within the season, with that trigger condition based on either forage height or aboveground biomass. The season-long methods can therefore allow multiple harvest events triggered within the specified season. The other five methods, in contrast, are one-time events that start on the specified date and have durations either specified or dependent on the forage harvest rate and current forage availability.

For all forage removal methods, the total standing herbage or "total standing biomass" consists of the sum of live aboveground biomass and standing dead biomass, often called standing residue. Figure 3 is a definition sketch illustrating the terms that are used to apportion live aboveground biomass; a similar sketch would apply to standing dead biomass. *Available forage* refers to standing biomass that is above a minimum height that reflects the eating characteristics of the grazing animals, although the minimum height may be set to 0 for operations that can remove all standing biomass. When the biomass is shorter than the minimum height for full removal, actual removal is progressively reduced relative to the specified removal, asymptotically reaching zero removal when the height reaches a fraction (default = 0.25, parameter name VEG_PERENN_ASYMP_PORTION_PARTIAL_REMOVAL) of the minimum height for full removal. If harvest of the forage is specified to be nonselective, the fraction of live biomass in the harvested forage is equal to the mass fraction of live aboveground biomass in the total standing biomass. The fraction of live biomass in forage is termed the *live portion* and can vary from 1 when forage is all live biomass to 0 when all forage is standing dead residue.

A portion of the total standing biomass may be considered protected from harvest (for example, by soiling) and is treated as though sequestered from harvest operations. This portion is termed *unaffected* (Fig. 3) and generally produces live biomass and residue as if it were never harvested. All affected herbage is considered harvested forage unless diverted into one of three

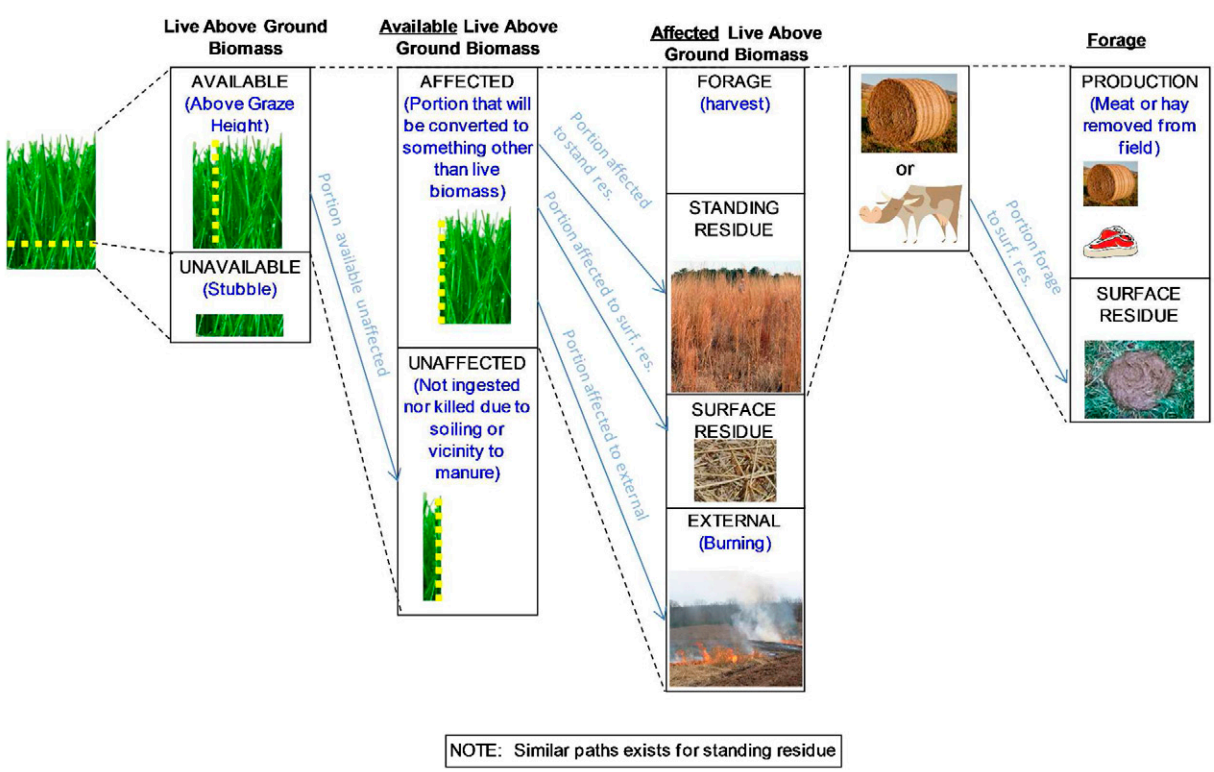

Fig. 3. Schematic flow diagram illustrating relationships between live aboveground, standing, and surface residue pools and partitioning during forage harvest processes.

Table 1. Processes used to define field operations in RUSLE2. Combinations of one or more of these processes may be saved—including default or user-defined parameter values—as named operations that are used to create management descriptions in RUSLE2. The focus of this study was on the 11th process.

Process	Process name	Process function†
1	no effect	causes RUSLE2 to display output information on certain dates
2	begin growth	identifies the vegetation description that RUSLE2 is to begin using on the date of an operation
3	kill vegetation	converts live aboveground biomass to standing residue and live roots to dead roots
4	flatten standing residue	represents mechanical flattening of standing residue
5	disturb surface	a complex process used to describe tillage operations that disturb the soil, bury residues, and create roughness
6	live biomass removed	removes live aboveground biomass without killing traditional RUSLE2 vegetation descriptions; generally followed by a begin growth process (2)
7	remove residue/cover	removes standing and surface (flat) residue; does not remove live aboveground biomass
8	add other cover	places materials like mulch or manure on the soil surface
9	add non-erodible cover	reduces or "shuts off" RUSLE2's erosion computations for certain periods such as when soils are frozen or covered with plastic
10	remove non-erodible cover	removes part or all existing non-erodible cover
11	perennial biomass and current standing residue removal	a complex process used to manage the new perennial vegetation descriptions; discussed in detail here
12	add permeable barrier	adds a temporary permeable barrier such as a compost sock
13	remove permeable barrier	removes an existing permeable barrier

† See USDA-ARS (2008b, Ch. 13) for more complete descriptions of Processes 1–10.

Table 2. Description of "perennial biomass and current standing residue removal" process parameters used in management descriptions. The unique RUSLE2 parameter name is listed in the third column because the parameter description in the first column is allowed to be changed in different user templates. In the RUSLE2 interface, the RUSLE2 name for a parameter can be seen by right-clicking on the parameter heading.

Parameter	Default	RUSLE2 parameter name	Description
Method of forage removal		OP_PTR	forage removal may be one time or season long; based on height or utilization; based on timing or stocking rate
Date		OP_DATE	date when the operation starts
Grazing season length, d	0	MAN_OP_VEG_NEW_BIOMASS_REM_SEASON	duration of season-long operations
Biomass forage rate, Mg ha^{-1} yr^{-1}	0	MAN_OP_VEG_NEW_BIOMASS_REM_RATE	forage removal rate
Biomass removal start height, m	0.15	MAN_OP_VEG_NEW_BIOMASS_REM_STARTHT	forage height that triggers the start of a harvest
Biomass removal end height, m	0.10	MAN_OP_VEG_NEW_BIOMASS_REM_ENDHT	forage height that ends a forage harvest period
Biomass removal duration, d	0	MAN_OP_VEG_NEW_BIOMASS_REM_DURON	duration of a forage harvest period
Biomass recovery duration, d	0	MAN_OP_VEG_NEW_BIOMASS_REM_DUROFF	interval between the end of a forage harvest period and the next forage harvest period
Biomass removal start mass, Mg ha^{-1}	0	MAN_OP_VEG_NEW_BIOMASS_REM_FORAGE_STARTMASS	forage biomass that triggers the start of a harvest period
Biomass removal utilization portion, %	0	MAN_OP_VEG_NEW_BIOMASS_REM_FORAGE_USEPORTION	forage removal fraction that ends a harvest period
Removal type	†	MAN_OP_VEG_NEW_BIOMASS_REMOVAL_HT_IMPACT	grazing animal type
Min. height for full removal, mm	51	MAN_OP_VEG_NEW_BIOMASS_MIN_HT_FULL_REMOVAL	height limit below which forage removal is reduced when vegetation is short, based on grazing animal type†
Biomass removal live forage (–1 = nonselective), %	–1	MAN_OP_VEG_NEW_BIOMASS_REM_LIVE_PORTION_REQUIRED	fraction of live biomass in harvested forage; nonselective harvest fractions equal proportions of live and standing dead in total aboveground biomass
Portion available unaffected, %	0	MAN_OP_VEG_NEW_BIOMASS_PORTION_AVAIL_UNAFFECTED	fraction of total aboveground biomass that is sequestered as if not harvested
Portion affected to external, %	0	MAN_OP_VEG_NEW_BIOMASS_REM_PORTION_AFFECTED_TO_EXTERNAL	fraction of affected biomass removal that is lost from the system and not counted as forage
Portion affected to surface residue, %	0	MAN_OP_VEG_NEW_BIOMASS_PORTION_AFFECTED_TO_SURF_RES	fraction of affected biomass that is converted to surface residue biomass and not counted as forage
Portion forage to surface residue, %	0	MAN_OP_VEG_NEW_BIOMASS_PORTION_FORAGE_TO_SURF_RES	fraction of forage harvest returned as surface residue (manure)
Portion affected to standing residue, %	0	MAN_OP_VEG_NEW_BIOMASS_PORTION_AFFECTED_TO_STAND_RES	fraction of affected biomass converted to standing dead
Portion standing to surfuce residue (affected and unaffected), %	0	MAN_OP_VEG_NEW_BIOMASS_PORTION_STAND_TO_SURF_RES	fraction of standing dead biomass converted to surface residue
Portion surface cover left after time on, %	0	MAN_OP_VEG_NEW_BIOMASS_SURF_COVER_LEFT	portion of existing and new surface residue cover that is left on the surface after harvest operation
Roughness after time on, m	0	MAN_OP_VEG_NEW_BIOMASS_FINAL_ROUGH	roughness height after harvest operation
Biomass removal post-forage clip height (0 = none), m	0	MAN_OP_VEG_NEW_BIOMASS_POST_FORAGE_CLIP_HT	height for a mowing operation that will be simulated at the end of each grazing harvest period

† Cattle, bison, deer, antelope, elk (default) = 51 mm; horse, mule, donkey, alpaca, llama = 38 mm; sheep, goats = 25 mm; not dependent (mowing, bare, etc.) = 0 mm.

additional categories requested by grazing land specialists, who indicated that these categories were needed to realistically describe haying and grazing systems. The extra categories are as follows and the default for each of these categories is zero: (i) affected live aboveground biomass removed from the system (lost to external) without becoming either forage or residue, applying primarily to standing dead biomass removed by burning; (ii) affected biomass directly converted to surface residue without being consumed as forage, reflecting material that falls out of an animal's mouth or out of the harvester, or losses due to shattered hay; and (iii) affected biomass converted directly to standing dead biomass, representing stems that die after their tops are removed. Additionally, some fraction of the biomass accounted for as harvested forage may be returned as surface residue, representing manure returns during grazing (Fig. 3).

Surface residues are assumed to be unavailable for forage harvest. However, harvest operations may disturb the surface by reducing the amount of existing surface residue through burial and by creating new surface roughness through foot traffic. The loss of surface residue is specified by defining the portion of existing surface residue plus surface residue mass added during this period that remains after the grazing operation. Similarly, the final random roughness created by the harvest operation may be specified. Again, the defaults of these effects are both zero, indicating no such impacts.

Finally, two additional process options apply to both affected and unaffected standing biomass. First, a portion of all standing residue may be converted to surface residue on the first day of a grazing period, reflecting mechanical trampling during grazing. Second, at the end of a grazing operation, pastures may be clipped to create a uniform sward height. These two effects are applied sequentially after standing residue is either created or removed through the "affected" process parameters described above. These two effects reduce the standing residue mass but do not affect current forage harvests.

Below are brief descriptions of the various forage removal methods and associated parameters. The one-time harvest methods are discussed first, followed by the season-long alternatives.

One-Time Harvest Methods

Set End Height, Rate. Forage removal starts on the date of the operation and continues at the specified forage removal rate until the live forage and standing dead residue are both equal to or shorter than the specified ending height. Forage removal stops as soon as this height condition is

Table 3. The RUSLE2 "perennial biomass and current standing residue removal" process parameters that may be set for each of the 13 alternative ways of specifying forage removal. Not setting the value will result in use of the default values specified in Table 2.

	Method of forage removal											
Process parameter	(1) Set end height, rate	(2) Set end height, time on	(3) Set rate, time on	(4) Set season, start height, end height, rate	(5) Set season, start height, end height, time on	(6) Set season, time on, time off, rate	(7) Set utilization, rate	(8) Set utilization, time on	(9) Set season, start height, utilization, rate	(10) Set season, start height, utilization, time on	(11) Set season, start mass, utilization, rate	(12) Set season, start mass, utilization, time on
Date	×	×	×	×	×	×	×	×	×	×	×	×
Grazing season length				×	×	×			×	×	×	×
Biomass forage rate	×		×	×		×	×		×		×	
Biomass removal start height				×	×				×	×		
Biomass removal end height	×	×		×	×							
Biomass removal duration		×	×		×	×		×		×		×
Biomass recovery duration						×						
Biomass removal start mass											×	×
Biomass removal utilization portion							×	×	×	×	×	×
Removal type (min. height for full removal)	×	×	×	×	×	×	×	×	×	×	×	×
Biomass removal live forage (−1 = nonselective)	×	×	×	×	×	×	×	×	×	×	×	×
Portion available unaffected	×	×	×	×	×	×	×	×	×	×	×	×
Portion affected to external	×	×	×	×	×	×	×	×	×	×	×	×
Portion affected to surface residue	×	×	×	×	×	×	×	×	×	×	×	×
Portion forage to surface residue	×	×	×	×	×	×	×	×	×	×	×	×
Portion affected to standing residue	×	×	×	×	×	×	×	×	×	×	×	×
Portion standing to surface residue (affected and unaffected)	×	×	×	×	×	×	×	×	×	×	×	×
Portion surface cover left after time on	×	×	×	×	×	×	×	×	×	×	×	×
Roughness after time on	×	×	×	×	×	×	×	×	×	×	×	×
Biomass removal post-forage clip height (0 = none)	×	×	×	×	×	×	×	×	×	×	×	×

met, so forage removal on the last day may be less than the amount called for by the specified removal rate.

Set End Height, Time On. Forage removal starts on the date of the operation and continues for the specified duration. The forage removal rate is recalculated each day such that the herbage will reach the specified final herbage height after the specified duration, so this option takes into account growth occurring during the harvest period. This alternative is commonly used to represent a single hay harvest or mowing on a specified date.

Set Rate, Time On. Forage removal starts on the date of the operation and continues for the specified duration. The forage removal rate is specified and continues as long as the herbage height is taller than the minimum height for full removal. If the vegetation falls below this height, forage removal is reduced and a forage shortfall is calculated as the difference between the specified and actual (reduced) forage removal rates.

Set Utilization, Rate. Forage removal starts on the date of the operation and continues at the specified forage removal rate until the total standing biomass existing at the start of the harvest period plus that produced during the harvest period has been reduced by the specified utilization percentage.

Set Utilization, Time On. Forage removal starts on the date of the operation and continues for the specified duration. The forage removal rate is calculated such that the sum of the total standing biomass at the start of the harvest period plus that produced during the harvest period is reduced by the specified utilization percentage over the duration.

Season-Long Harvest Methods

With all season-long harvest methods, the harvest season begins on the date of the operation and continues for the specified season duration, which may be as little as 1 d or as long as 365 d or longer. A harvest period within that season begins when a specified starting criterion is met. Each harvest period is calculated as with the one-time harvest methods described above. After each harvest period, the underlying growth model continues modeling vegetation birth and death as described by Dabney and Yoder (2012) until the governing starting condition is again satisfied, at which point another harvest period begins. The process is repeated for the duration of the harvest season. If the "Biomass removed post-forage clip height" option is set to a value >0, then a mowing operation at the specified height is simulated at the end of each harvest period. Also, for season-long harvest methods, the effect of the "portion surface cover left after time on" varies between management schemes that are based on duration (time on) and those that depend on height or utilization portion. In the former case, the residue reduction is calculated for each harvest period, whereas in the latter case the residue reduction percentage applies to the entire season because there is no way to predetermine the length of the harvest periods.

The specific alternative management options for the season-long methods are described below. In all of these, the sequence is repeated throughout the duration of the harvest season.

Set Season, Start Height, End Height, and Rate. A harvest period within the specified season begins when the standing biomass exceeds the specified start height. Harvest continues at the specified forage removal rate until the live forage and standing dead residue are both equal to or shorter than the specified ending height. Another harvest period begins when, due to growth, the modeled standing biomass again exceeds the specified start height.

Set Season, Start Height, End Height, Time On. A harvest period within the specified season begins when the standing biomass exceeds the start height. Harvest then continues for the specified harvest period duration. The forage removal rate is calculated such that the herbage will reach the specified final herbage height after the specified duration. Another harvest period begins when, due to growth, the modeled standing biomass again exceeds the specified start height.

Set Season, Time On, Time Off, Rate. A harvest period begins on the date of the setting operation, and forage removal takes place at the specified rate for the duration specified as "time on." This harvest period is followed by a "time off" rest period, and the process is repeated until interrupted by the specified season end. If the herbage height during a harvest period falls below the minimum height for full removal, the actual harvest rate will fall below the desired target and a shortfall will be calculated.

Set Season, Start Height, Utilization, Rate. A harvest period within the specified season begins when the standing biomass exceeds the start height. Harvest then continues at the forage removal rate specified until the total standing biomass existing at the start of the harvest period plus that produced during the harvest period has been reduced by the specified utilization percentage. Another harvest period begins when, due to growth, the modeled standing biomass again exceeds the specified start height.

Set Season, Start Height, Utilization, Time On. A harvest period within the specified season begins when the standing biomass exceeds the start height. Harvest then continues for the specified duration. The forage removal rate is calculated such that after the specified duration ("time on"), the total standing biomass existing at the start of the harvest period plus that produced during the harvest period has been reduced by the specified utilization percentage. Another harvest period begins when, due to growth, the modeled standing biomass again exceeds the specified start height.

Set Season, Start Mass, Utilization, Rate. A harvest period within the specified season begins when the standing biomass exceeds the specified start mass. Harvest then continues at the specified forage removal rate until the total standing biomass existing at the start of the harvest period plus that produced during the harvest period has been reduced by the specified utilization percentage. Another harvest period begins when, due to growth, the modeled standing biomass again exceeds the specified start mass.

Set Season, Start Mass, Utilization, Time On. A harvest period within the specified season begins when the standing biomass exceeds the specified start mass. Harvest then continues for the specified duration. The forage removal rate is calculated such that after the specified duration ("time on"), the total standing biomass existing at the start of the harvest period plus that produced during the harvest period has been reduced by the specified utilization percentage. Another harvest period begins when, due to growth, the modeled standing biomass again exceeds the specified start mass.

Forage Results Reported at the Profile Level

RUSLE2 outputs several levels of biomass and forage harvest results: totals and averages for the entire year, totals and averages for each harvest period, and daily values. If there are different land management systems on different segments (portions) of a hillslope, annual profile results are spatial averages across all segments, harvest period results are based on only the top segment

Table 4. Profile-level forage harvest output RUSLE2 parameter names, descriptive text, and default units.

Profile annual average forage results	Description
ANNUAL_TOTAL_BIOMASS_REMOVAL	avg. annual forage harvest, Mg ha^{-1} yr^{-1}
AVG_TOTAL_FORAGE_REMOVAL_AGE	avg. forage age, d
AVG_TOTAL_FORAGE_REMOVAL_SHORTFALL	total shortfall, Mg ha^{-1} yr^{-1}
Segment Harvest Period Forage Results	
SLOPE_MAN_PERENNN_NUM_HARV_PERIODS	number
SLOPE_MAN_PERENNN_HARV_PERIOD_START_DATE	start date (mo/d/yr)
SLOPE_MAN_PERENNN_HARV_PERIOD_LENGTH	length of removal, d
SLOPE_MAN_PERENNN_HARV_PERIOD_DAYS_OFF	length of rest period, d
SLOPE_MAN_PERENNN_HARV_PERIOD_MASS	harvest, Mg ha^{-1}
SLOPE_MAN_PERENNN_HARV_PERIOD_QUALITY	live portion, fraction
SLOPE_MAN_PERENNN_HARV_PERIOD_AGE	age, d
SLOPE_MAN_PERENNN_HARV_PERIOD_RATE	avg. harvest rate, kg ha^{-1} d^{-1}†
SLOPE_MAN_PERENNN_HARV_PERIOD_SHORTFALL	shortfall, Mg ha^{-1}
Segment Daily Forage Results	
SEG_SIM_DAY_LIVE_BIOMASS	live biomass, kg ha^{-1}
SEG_SIM_DAY_STAND_MASS_SUM	standing residue mass, kg ha^{-1}
SEG_SIM_DAY_TOTAL_STAND_MASS_SUM	total standing mass, kg ha^{-1}
SEG_SIM_DAY_PERENN_VEG_LIVE_HEIGHT	live height, cm
SEG_SIM_DAY_COVER_MASS_SUM	total surface residue, kg ha^{-1}
SEG_SIM_DAY_NET_SURF_COV	net surface cover, %
SEG_SIM_DAY_FULL_DEPTH_LIVE_ROOTS	full-depth live roots, kg ha^{-1}
SEG_SIM_DAY_FULL_DEPTH_DEAD_ROOTS	full-depth dead roots, kg ha^{-1}
SEG_SIM_DAY_LIVE_SURF_COVER	live surface cover, %
SEG_SIM_DAY_PERENN_VEG_LIVE_HARVEST_RATE	live harvest, kg ha^{-1} d^{-1}†
SEG_SIM_DAY_PERENN_VEG_RES_HARVEST_RATE	residue harvest, kg ha^{-1} d^{-1}†
SEG_SIM_DAY_PERENN_VEG_TOTAL_HARVEST_RATE	total harvest, kg ha^{-1} d^{-1}†
SEG_SIM_DAY_PERENN_VEG_FORAGE_REMOVAL_SHORTFALL	forage shortfall, kg ha^{-1} d^{-1}†

† One animal unit = 11.8 kg d^{-1}.

of the profile, and daily results are reported for each segment. For simplicity, we discuss only a one-segment hillslope profile with uniform land management, which is still the most common use of RUSLE2.

Three annual average forage values are reported: average annual forage harvest, average forage age, and average annual forage shortfall (Table 4). Forage age is calculated as the mass weighted average age of live and dead herbage removed as forage, where the age of harvested standing dead residue is set equal to the lifespan of the forage that produced the standing dead residue (Dabney and Yoder, 2012). Forage shortfall during a harvest period is calculated only for operations that use a forage removal method specifying rate and time on, and is the sum of the shortfalls for each day. Shortfall is calculated only for these removal methods because when forage harvest is based on height or utilization portion, forage removal stops when the criterion to end a grazing period is met, so there is no shortfall.

Harvest period results (Table 4) include the start date of each harvest, the duration of each period, the total forage harvested during the period, the total period shortfall, the average forage harvest rate during the period, the duration of the "rest" interval (time of no harvest) between harvest periods, and two quality indicators for each harvest period: the live portion (fraction of live forage in total herbage harvested) and the average age of harvested forage.

Daily forage results (Table 4) include aboveground live biomass and live biomass height, standing residue mass, surface residue mass and associated cover percentage, full depth live and dead root biomass, and daily harvests of live biomass, standing dead biomass, and forage shortfalls. These daily values are useful in visualizing output behavior because the RUSLE2 graphical user interface (GUI) includes numerous utilities such as graphing, changing units, changing significant figures, or calculating summary statistics. These functions are made available by right-clicking the mouse on the desired table column heading.

Forage Removal Processes at Operation and Vegetation Levels

In addition to inputs described above at the management level, forage removal process parameters may also be specified within either operation or vegetation descriptions (Fig. 2).

Harvest Operation Descriptions

To facilitate the development of management descriptions, harvest operations that call on the new "perennial biomass and current standing residue removal" process may be named and saved with different default parameter values (Table 5) for later reuse. When later used within a management description, the forage removal process parameters saved in the operation become the corresponding process parameters in the active management, although these default values—except for the forage removal method—may be overwritten at the management level to reflect specific details. For example, in the NRCS's new forage database, an operation named "Grazing, continuous, set season, rate" uses the "set season, time on, time off, and rate" forage removal method, has a grazing season length of 365 d, a base forage removal rate of 11 Mg ha^{-1} yr^{-1}, a base removal duration of 270 d, converts 5% of

Table 5. The RUSLE2 parameter names used to describe "perennial biomass and current standing residue removal" process options when used within operation descriptions and within the vegetation description wizard.

Parameter description	Operation (set defaults for process options)	Wizard (used to test vegetation behavior)
Date		VEG_PERENN_FORAGE_OP_DATE
Method of forage removal	OP_BIOMASS_NEW_REM_CHOICE	VEG_PERENN_FORAGE_CHOICE
Grazing season length	OP_BIOMASS_NEW_REM_FORAGE_SEASON	VEG_PERENN_FORAGE_SEASON
Biomass forage rate	OP_BIOMASS_NEW_REM_OP_FORAGE_RATE	VEG_PERENN_OP_FORAGE_RATE
Biomass removal start height	OP_BIOMASS_NEW_REM_FORAGE_STARTHT	VEG_PERENN_FORAGE_STARTHT
Biomass removal end ht	OP_BIOMASS_NEW_REM_FORAGE_ENDHT	VEG_PERENN_FORAGE_ENDHT
Biomass removal duration	OP_BIOMASS_NEW_REM_FORAGE_DURON	VEG_PERENN_FORAGE_DURON
Biomass recovery duration	OP_BIOMASS_NEW_REM_FORAGE_DUROFF	VEG_PERENN_FORAGE_DUROFF
Biomass removal start mass	OP_BIOMASS_NEW_REM_FORAGE_STARTMASS	VEG_PERENN_STARTMASS
Biomass removal utilization portion	OP_BIOMASS_NEW_REM_FORAGE_USEPORTION	VEG_PERENN_USEPORTION
Removal type	OP_BIOMASS_NEW_REM_REMOVAL_HT_IMPACT	VEG_PERENN_REMOVAL_HT_IMPACT
Min. height for full removal		VEG_PERENN_MIN_HT_FULL_REMOVAL
Biomass removal live forage (−1 = nonselective)	OP_BIOMASS_NEW_REM_PORTION_LIVE_REQUIRED	VEG_PERENN_PORTION_LIVE_REQUIRED
Portion available unaffected	OP_BIOMASS_NEW_REM_PORTION_AVAIL_UNAFFECTED	VEG_PERENN_PORTION_AVAIL_UNAFFECTED
Portion affected to external	OP_BIOMASS_NEW_REM_PORTION_AFFECTED_TO_EXTERNAL	VEG_PERENN_PORTION_AFFECTED_TO_EXTERNAL
Portion affected to surface residue	OP_BIOMASS_NEW_REM_PORTION_AFFECTED_TO_SURF_RES	VEG_PERENN_PORTION_AFFECTED_TO_SURF_RES
Portion forage to surface residue	OP_BIOMASS_NEW_REM_PORTION_FORAGE_TO_SURF_RES	VEG_PERENN_PORTION_FORAGE_TO_SURF_RES
Portion affected to standing residue	OP_BIOMASS_NEW_REM_PORTION_AFFECTED_TO_STAND_RES	VEG_PERENN_PORTION_AFFECTED_TO_STAND_RES
Portion standing to surface residue (affected and unaffected)	OP_BIOMASS_NEW_REM_PORTION_STAND_TO_SURF_RES	VEG_PERENN_PORTION_STAND_TO_SURF_RES
Disturbs surface?	OP_BIOMASS_NEW_REM_DISTURBS_SURFACE	
Portion surf cover left after time on	OP_BIOMASS_NEW_REM_RES_SURF_COVER_LEFT	VEG_PERENN_FORAGE_PORTION_FLAT_RES_LEFT
Roughness after time on	OP_BIOMASS_NEW_REM_FINAL_ROUGH	
Biomass removal post-forage clip height (0 = none)	OP_BIOMASS_NEW_REM_FORAGE_CLIP_HT	VEG_PERENN_POST_FORAGE_CLIP_HT

affected biomass to surface residue and 10% to standing residue, 8% of forage removed is returned as surface residue (manure), and the operation retains 85% of the existing cover and creates a random roughness of 13 mm after the grazing season.

The Vegetation "Wizard"

The vegetation wizard is a program object developed to facilitate input parameterization of dynamic vegetation descriptions for the plant growth model described by Dabney and Yoder (2012). The wizard includes a set of management options or "pseudo-operations" and a set of forage result outputs similar to those used at the profile level. Some parameters—such as soil roughness—that relate to soil erosion but not to forage or residue production are not implemented within the vegetation wizard (Table 5). A trained specialist developing a vegetation description uses these pseudo-operations and forage production results to efficiently adjust vegetation model input parameters and examine the resulting herbage growth while bypassing the RUSLE2 erosion calculations. Once the vegetation behavior in the wizard is deemed satisfactory, the specialist hits the "Apply" button and the resulting forage growth chart, yield level, and underlying crop growth model parameter values are written into the RUSLE2 vegetation description that can be saved under a desired name. Pseudo-operation parameter values used and stored within the vegetation wizard (Table 5) have no effect on the vegetation computations made at the profile level, which are controlled by management-level parameter values (Table 2).

When a vegetation description is called into a management description, the associated vegetation yield level (VEG_NUM_HARV_UNITS) becomes the default yield level in the management (MAN_OP_VEG_NUM_HARV_UNITS), but this default yield may be overwritten in the management, and the management can then be stored with a unique descriptive name. When a management is called into a hillslope profile, RUSLE2 uses management-level information (Table 2) to determine the daily forage harvest, residue, canopy, biomass, and roughness values and finely calculates the resulting runoff, soil loss, and sediment delivery (Fig. 2). If the user changes the yield level or other management option at the profile level, the RUSLE2 calculation engine determines what results are dependent on the parameter changed and recalculates those affected results.

Management Involving Vegetation Mixtures

As reviewed by Dabney and Yoder (2012), RUSLE2 allows only one vegetation to be actively growing at any time. Using only "old-style" vegetation descriptions, when a new vegetation is called with Process 2 (begin growth, Table 1), the old vegetation is assumed killed and any decreases in live above- or belowground biomass pools between the existing and new vegetation descriptions get added to the corresponding above- and belowground residue pools. Old-style vegetation and its residues are managed using Processes 6 (live biomass removed) or 7 (remove residue/cover). In contrast, new-style "modeled" vegetation (MOD_VEG) forage harvest and residue management is accomplished using Process 11 (Perennial biomass and current standing residue removal), as described here. When management descriptions are developed that involve a combination of MOD_VEG and old-style vegetation descriptions without an explicit Process 3 (kill vegetation) before a Process 2 (begin growth), special procedures have been implemented to allow residues from the old-style vegetation to be managed with Process 11.

For example, if an old-style grain crop is rotated with a MOD_VEG perennial forage crop, the perennial vegetation may not be killed. Similarly, if a winter annual cover crop is planted into a dormant perennial vegetation, the perennial will not be killed. To facilitate developing descriptions of such management systems, a special class of vegetation, termed a "shadow" vegetation, has been implemented to hold the biomass of the existing vegetation when the growth of a different vegetation type is begun with Process 2 (begin growth) and either the existing or new vegetation is a MOD_VEG and no Process 3 (kill vegetation) is specified. If the existing vegetation is a MOD_VEG, the biomass in existing vegetation pools (shoots, active roots, and woody roots) gets transferred to the corresponding pools of the shadow vegetation. The shadow vegetation does not grow but rather gradually dies according to the lifespans of each pool. If the existing vegetation is an old-style description, then RUSLE2 creates a shadow MOD_VEG using default values for pool lifespans (45 d for aboveground growth, 45 d for active roots). If the beginning vegetation is a MOD_VEG, the new vegetation is set up as if there were no existing vegetation, and the actual and shadow vegetation coexist until the live shadow vegetation pools have died. In any case, residues created during the death of a shadow MOD_VEG are managed with operations involving Process 11 (perennial biomass and current standing residue removal) in the same manner as all residues.

APPLICATIONS

To test the validity of the approach and the applicability of the model as controlled by the new harvest procedures, the model results were compared with a series of published forage studies.

Bahiagrass Pasture in Florida

Using data from a series of studies (Interrante et al., 2009) involving Pensacola bahiagrass (*Paspalum notatum* Flügge) grown in Gainesville, FL, monthly growth percentages for Pensacola bahiagrass were developed for the RUSLE2 vegetation growth model (Table 6). This vegetation description was used in management descriptions created to mimic the treatments evaluated by Dubeux et al. (2006a, 2006b) and Stewart et al. (2007) that evaluated litter creation, litter decomposition, and animal performance in continuously stocked Pensacola bahiagrass pastures as a function of three levels of management intensity. These studies defined management intensity in terms of combinations of stocking rate and N fertilization level: low (40 kg N ha^{-1} yr^{-1} and 1.2 animal units [AU] ha^{-1}), moderate (120 kg N ha^{-1} yr^{-1} and 2.7 AU ha^{-1}), and high (360 kg N ha^{-1} yr^{-1} and 4.0 AU ha^{-1}), where one AU equaled 500 kg ha^{-1} live weight. The low intensity system approximated an average bahiagrass management for cow–calf operations in Florida, the moderate system represented the upper range of current practices, and the high system was more intensive than current practices. Plots were grazed by two yearling heifers (*Bos taurus*, initial average live weight of 327 kg) per plot from May—after the accumulation of sufficient herbage mass to support livestock—through October. The plot size was varied from 1.0 to 0.33 ha to achieve the desired stocking rates. The average animal weight gains reported every 28 d were used to determine the effective stocking rate, and forage removal rates were adjusted under the assumption that forage consumption was equal to 2.2%

Table 6. The RUSLE2 parameter values used to describe the three vegetation types in the application studies, including the monthly percentage of net primary productivity (NPP_m), the lifespan of aboveground vegetation (l_s), the fraction of active roots becoming woody roots after their lifespan is reached (f), and the target root/shoot ratio (RS*).

Month	NPP_m	l_s	f	RS*
		d		
		Bahiagrass, Florida †		
Jan.	2	60	30	2
Feb.	3	60	30	2
Mar.	4	60	30	2
Apr.	9	60	30	2
May	15	60	30	2
June	16	60	30	2
July	16	60	30	2
Aug.	14	60	30	2
Sept.	8	60	30	2
Oct.	6	60	30	2
Nov.	4	60	30	2
Dec.	3	60	30	2
		Bermudagrass, Georgia ‡		
Jan.	1	60	30	2
Feb.	3	60	30	2
Mar.	7	60	30	2
Apr.	9	60	30	2
May	16	60	30	2
June	17	60	30	2
July	17	60	30	2
Aug.	12	60	30	2
Sept.	10	60	30	2
Oct.	4	60	30	2
Nov.	2	60	30	2
Dec.	2	60	30	2
		Ryegrass, UK§		
Jan.	2	60	30	2
Feb.	2	60	30	2
Mar.	8	60	30	2
Apr.	16	60	30	2
May	17	60	30	2
June	16	60	30	2
July	13	60	30	2
Aug.	11	60	30	2
Sept.	6	60	30	2
Oct.	4	60	30	2
Nov.	3	60	30	2
Dec.	2	60	30	2

† Target annual net primary productivity (NPP_T): low intensity = 10.7, moderate intensity = 11.2, high intensity = 12.2 Mg ha^{-1} yr^{-1}; maximum canopy height achieved at maturity (H_{max}) = 45 cm; potential cut height (H_p) = 10 cm; envelope midpoint portion (h_m) = 0.45; base decomposition constant (φ) = 0.017 d^{-1} (for a detailed discussion of these parameters, see Dabney and Yoder, 2012).

‡ NPP_T: low grazing pressure = 13.5, high grazing pressure = 11.5, hay = 13.0, unharvested = 13.5 Mg ha^{-1} yr^{-1}; H_{max} = 30 cm; H_p = 5.1 cm; h_m = 0.36; φ = 0.017 d^{-1}.

§ NPP_T = 12.0 Mg ha^{-1} yr^{-1}; H_{max} = 40 cm; H_p = 5 cm; h_m = 0.35; φ = 0.017 d^{-1} (see Dabney and Yoder, 2012).

Table 7. The RUSLE2 "perennial biomass and current standing residue removal" process parameters used to simulate harvest of the moderate intensity bahiagrass pasture system (Dubeux et al., 2006b; Stewart et al., 2007).

Process parameter	Method of forage removal					
	Set rate, time on	Set rate, time on	Set rate, time on	Set rate, time on	Set rate, time on	Set rate, time on
Date	18 May	15 June	13 July	10 Aug.	7 Sept.	5 Oct.
Grazing season length, d	NA†	NA	NA	NA	NA	NA
Forage rate, kg ha^{-1} d^{-1}	29.5	30.6	31.2	32.7	33.5	34.4
Biomass removal start height, cm	NA	NA	NA	NA	NA	NA
Biomass removal end height, cm	NA	NA	NA	NA	NA	NA
Removal duration, d	28	28	28	28	28	28
Biomass recovery duration	NA	NA	NA	NA	NA	NA
Biomass removal start mass	NA	NA	NA	NA	NA	NA
Biomass removal utilization portion	NA	NA	NA	NA	NA	NA
Min. height for full removal, mm	51	51	51	51	51	51
Biomass removal live forage (–1 = nonselective)	–1	–1	–1	–1	–1	–1
Portion available unaffected	0	0	0	0	0	0
Portion affected to external	0	0	0	0	0	0
Portion affected to surface residue	0	0	0	0	0	0
Portion forage to surface residue	8	8	8	8	8	8
Portion affected to standing residue	0	0	0	0	0	0
Portion standing to surface residue (affected and unaffected)	90	0	0	0	0	0
Portion surface cover left after time on	100	100	100	100	100	100
Roughness after time on (0 = not modeled)	0	0	0	0	0	0
Biomass removal post-forage clip height (0 = none)	0	0	0	0	0	0

† NA, this parameter is not used for the specified method, but the entire list is included for completeness.

of body weight and an animal unit was equivalent to consumption of 11.8 kg ha^{-1} d^{-1}. Litter was defined as dead plant material on the surface of the soil, no longer attached to the plant, which is considered surface residue in RUSLE2. Five times per grazing year, at 28-d intervals, the existing litter was collected and the rate of litter creation was determined by placing exclusion cages over the collection area and collecting litter from the same areas 14 d later.

Dubeux et al. (2006a) determined litter decomposition rates using 128-d incubation in litter bags. They found that mass loss was rapid early in the incubation (15% loss during the first 8 d of incubation), after which further decomposition was much slower. After the initial rapid loss, the effective litter decomposition coefficients were 0.0016 g g^{-1} d^{-1} for low intensity management, 0.0021 g g^{-1} d^{-1} for moderate intensity management, and 0.003 g g^{-1} d^{-1} for high intensity management. These decomposition coefficients are considerably lower than the single-pool decomposition coefficient 0.017 d^{-1} used for "grass forage" residue degradation under ideal conditions in the official RUSLE2 database (NRCS, 2012).

Using the RUSLE2 "grass forage" residue type and the Alachua County, Florida, climate description from the official NRCS RUSLE2 database (NRCS, 2012), harvest operations were adjusted every 28 d based on the stocking rate for each treatment using the "set rate, time on" forage removal operation (Table 7). The RUSLE2 forage production target (Dabney and Yoder, 2012) was adjusted to approximate the standing herbage. In the harvest operations, all parameter settings were left at default values except that 8% of consumed forage was returned as surface residue to simulate manure additions and the portion of standing residue converted to surface residue was set to 90% for the first grazing operation to reflect the trampling of standing dead residue that had accumulated during the winter and early spring (Table 7). RUSLE2 predicted net surface residue accumulation (balance of litter creation and decomposition) adequately (Fig. 4) to provide reasonable soil erosion estimates. Across all three management systems, the Nash–Sutcliffe model efficiency coefficients (Moriasi et al., 2007) were simultaneously 0.25 (n = 15) for predicted surface residue mass and 0.27 (n = 18) for standing herbage. Crude protein (CP) and in vitro digestible organic matter (IVDOM), measured on grab samples collected from the top 5 cm of each pasture sward, were compared with the two forage quality indicators tracked by the RUSLE2 forage model: live portion and forage age (Table 4). The average forage age was found to be better correlated with the measured quality factors and was better correlated with IVDOM (R^2 = 0.76) than with CP (R^2 = 0.31) (Fig. 5).

Bermudagrass Hay or Pasture in Georgia

Franzluebbers et al. (2004) and Stuedemann and Franzluebbers (2007) reported the response of Coastal bermudagrass [*Cynodon dactylon* (L.) Pers.] grown in the Southern Piedmont resource area in Georgia during the 5-yr period from 1994 to 1998 to four management systems: unharvested, grazed to maintain 4.5 Mg ha^{-1} herbage (low grazing pressure), grazed to maintain 2.5 Mg ha^{-1} (high grazing pressure), or cut for hay at a height of 5 cm at monthly intervals during the summer. These studies also compared three nutrient sources, but only the inorganic N plots are considered here. The plots averaged 0.69 ha and were grazed by yearling Angus steers during a 140-d period from mid-May until early October each year. Each plot had three steers permanently assigned, and additional steers were added and removed at 28-d intervals as needed to maintain sward standing herbage at the desired herbage biomass levels. Monthly hay and uncut forage biomass were determined from the hayed and unharvested exclosures (100 m^2 each) located side by side in paired low- and high-pressure paddocks. Unharvested areas were cut and the resulting residues left in place at the end of each growing season. All grazed paddocks were mowed to a 10-cm height in late April immediately following collection of the initial forage and surface residue samples.

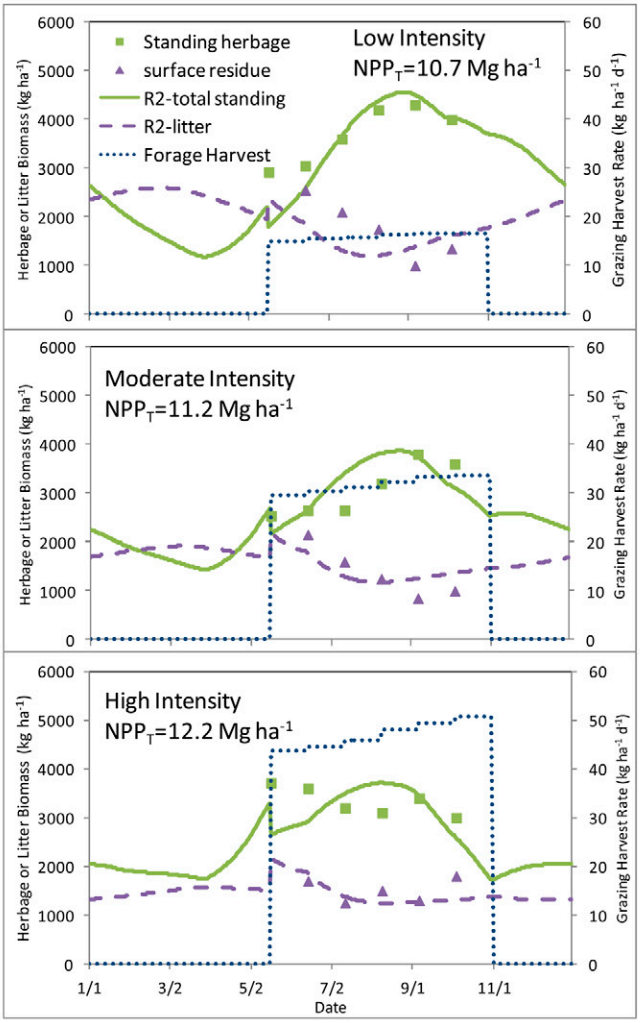

Fig. 4. Observed (points) Pensacola bahiagrass herbage and surface residue (Dubeux et al., 2006b) and RUSLE2 (R2) predictions (lines) for a single vegetation description with monthly growth percentages from Interrante et al. (2009) but varying management intensity, through potential yield (target net primary productivity, NPP$_T$) and reported stocking rates (Stewart et al., 2007).

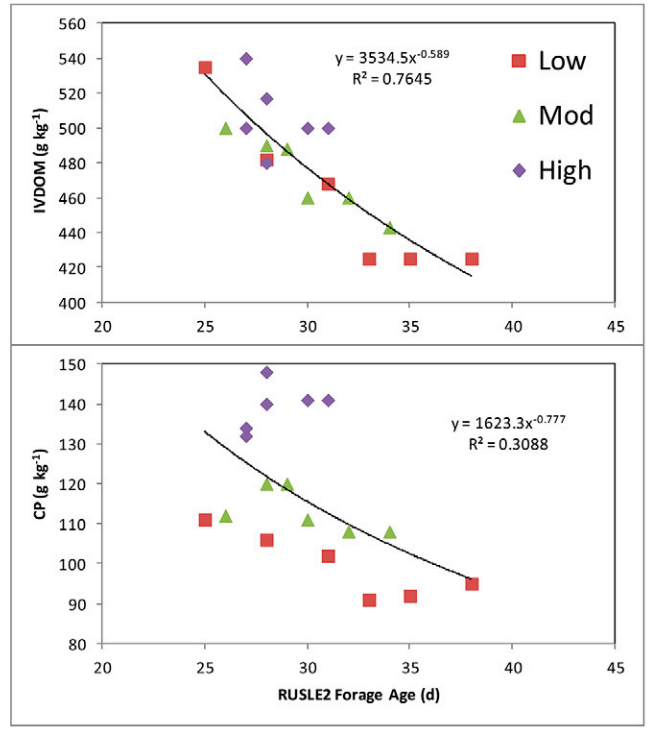

Fig. 5. The "Forage Age" RUSLE2 parameter was better correlated with observed in vitro digestible organic matter (IVDOM) than with herbage crude protein (CP) reported for samples collected from the top 5 cm of the canopy of continuously grazed Pensacola bahiagrass pastures receiving three levels of management intensity (Stewart et al., 2007).

In these and related studies (Franzluebbers et al., 2001; Franzluebbers and Studemann, 2009), surface residue was collected after removing vegetation at a height of about 4 cm, and the plant crown material was harvested and included along with litter in the surface residue pools. Because this is different from the convention used in RUSLE2, where stubble vegetation is part of the standing biomass pool, the observed residue biomass estimates were adjusted before comparing observations with RUSLE2 predictions, as follows. The reported residue biomass was decreased and the standing biomass was increased by a quantity calculated as the 4-cm cutting height multiplied by the "aboveground biomass density" calculated as the ratio of forage biomass divided the forage height above 4 cm. Because the vegetation height was not reported, the RUSLE2-predicted biomass height at the time of each sampling was used as an approximation. A second adjustment to the residue biomass was made to correct for soil contamination included in the reported residue biomass. The C fraction of the forage and the residue were calculated as the product of the C/N ratio times the N content. The C fraction was found to be (mean ± standard deviation) 0.46 ± .03 for the forage and 0.30 ± 0.05 for the surface residue. Adjusted surface residue masses were calculated under the assumption that true residue biomass had a C fraction of 0.50 and that surface soil contamination (duff) had a C fraction of 0.12.

Monthly herbage accumulation patterns from April through October from all four treatments were used to develop monthly primary production percentages for a RUSLE2 vegetation description (Table 6). Although bermudagrass is dormant during the winter months at the research location, the monthly growth percentages derived needed to reflect all vegetation grown on the site, including the growth of volunteer winter weeds. Winter weed growth and common bermudagrass encroachment during the late summer were greater in the high grazing pressure and hay harvest treatments than in the other treatments (Franzluebbers et al., 2004).

The amount of forage removed during each grazing period was determined based on the average body weight of grazing steers, the number of steers, and the average daily gain in body weight during each 28-d grazing period (National Research Council, 1996) and was between 2.1 and 2.4% of body weight. Using the RUSLE2 "grass forage" residue type and the Oconee County, Georgia, climate description from the official NRCS RUSLE2 database (NRCS, 2012), harvest operations were developed for each of the four treatments. Pasture forage harvest rates were adjusted every 28 d based on the stocking rate for each grazing treatment using the "set rate, time on" forage removal operation (Table 8). For the hay and unharvested treatments, the "set end height, time on" option was used on appropriate dates. To match the average herbage biomass during the growing season and the residue biomass at the start and end of the grazing season required that the potential NPP target be set higher for the low grazing pressure treatment (13.5 Mg ha^{-1}) than for the high grazing pressure treatment (11.5 Mg ha^{-1}) or the hay treatment (12.0 Mg ha^{-1}). Further, to

Table 8. The RUSLE2 “perennial biomass and current standing residue removal” process parameters used to simulate harvest of the low grazing pressure bermudagrass pasture system (Stuedemann and Franzluebbers, 2007).

Process parameter	Method of forage removal					
	Set end height, time on	Set rate, time on	Set rate, time on	Set rate, time on	Set rate, time on	Set rate, time on
Date	25 Apr.	17 May	14 June	12 July	9 Aug.	6 Sept.
Grazing season length, d	NA†	NA	NA	NA	NA	NA
Forage rate, kg ha^{-1} d^{-1}	NA	28.6	45.2	58.2	54.5	50.0
Biomass removal start height, cm	NA	NA	NA	NA	NA	NA
Biomass removal end height, cm	10	NA	NA	NA	NA	NA
Removal duration, d	1	28	28	28	28	28
Biomass recovery duration	NA	NA	NA	NA	NA	NA
Biomass removal start mass	NA	NA	NA	NA	NA	NA
Biomass removal utilization portion	NA	NA	NA	NA	NA	NA
Min. height for full removal, mm	51	51	51	51	51	51
Biomass removal live forage (–1 = nonselective)	–1	–1	–1	–1	–1	–1
Portion available unaffected	0	0	0	0	0	0
Portion affected to external	0	0	0	0	0	0
Portion affected to surface residue	100	0	0	0	0	0
Portion forage to surface residue	0	8	8	8	8	8
Portion affected to standing residue	0	0	0	0	0	0
Portion standing to surface residue (affected and unaffected)	0	0	0	0	0	0
Portion surface cover left after time on	100	100	100	100	100	100
Roughness after time on (0 = not modeled)	0	0	0	0	0	0
Biomass removal post-forage clip height (0 = none)	0	0	0	0	0	0

† NA, this parameter is not used for the specified method, but the entire list is included for completeness.

approximate the unharvested treatment behavior (Fig. 6), the potential NPP target was set to 12.0 Mg ha^{-1} and the single-pool residue decomposition coefficient was lowered from the 0.017 d^{-1} for grass forage residue to 0.008 d^{-1}, a value similar to that of straw, to reflect the likelihood that unharvested bermudagrass residues had a greater ratio of stem to leaf mass, a higher C/N ratio, lower digestibility, and a coarser particle size than typical grass forage residue (Liu et al., 2011). Under actual management, the RUSLE2 growth model estimated NPP was 12.6 Mg ha^{-1} for high grazing pressure, 16.6 Mg ha^{-1} for low grazing pressure, 13.6 Mg ha^{-1} for

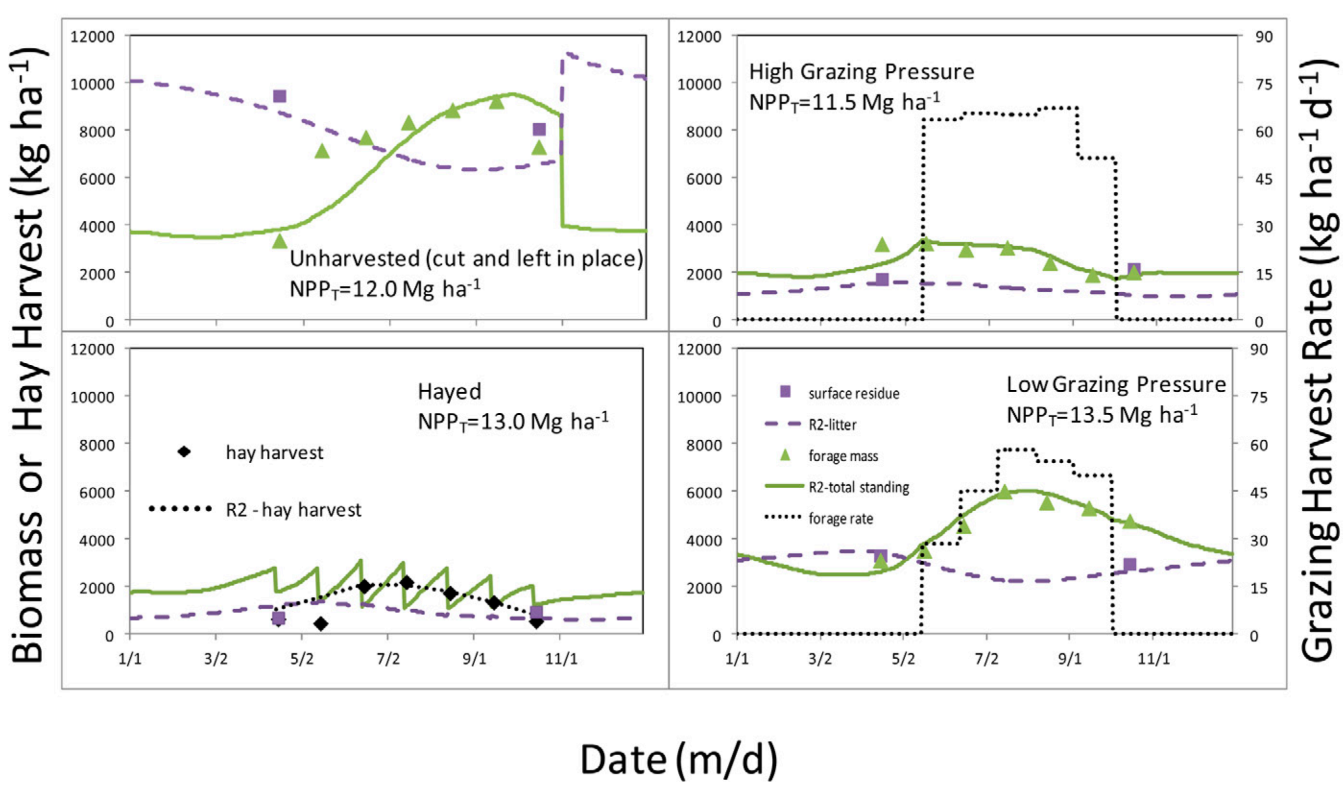

Fig. 6. Comparison of RUSLE2 (R2) target net primary productivity, NPP$_T$, and predicted standing bermudagrass biomass, surface residue, and grazing or hay harvests (lines), compared with 5-yr average values (points) reported by Franzluebbers et al. (2004) and Stuedemann and Franzluebbers (2007).

Table 9. The RUSLE2 "perennial biomass and current standing residue removal" process parameters used to simulate harvest of the C4 perennial ryegrass pasture system (Carton et al., 1988a).

Process parameter	Method of forage removal						
	Set season, start height, end height, rate	Set end height, time on	Set rate, time on	Set rate, time on	Set rate, time on	Set rate, time on	Set season, start height, end height, rate
Date	15 Mar.	15 Aug.	18 Sept.	16 Oct.	12 Nov.	18 Dec.	15 May
Grazing season length, d	105	NA†	NA	NA	NA	NA	155
Forage rate, kg ha^{-1} d^{-1}	100	28.6	700	700	700	700	100
Biomass removal start height, cm	7	NA	NA	NA	NA	NA	7
Biomass removal end height, cm	7	5	NA	NA	NA	NA	7
Removal duration, d	NA	1	1	1	1	1	NA
Biomass recovery duration	NA	NA	NA	NA	NA	NA	NA
Biomass removal start mass	NA	NA	NA	NA	NA	NA	NA
Biomass removal utilization portion	NA	NA	NA	NA	NA	NA	NA
Min. height for full removal, mm	38	38	51	51	51	51	38
Biomass removal live forage (–1 = nonselective)	–1	–1	–1	–1	–1	–1	–1
Portion available unaffected	0	0	0	0	0	0	0
Portion affected to external	0	0	0	0	0	0	0
Portion affected to surface residue	100	0	30	30	30	30	0
Portion forage to surface residue	0	0	0	0	0	0	0
Portion affected to standing residue	0	0	30	30	30	30	0
Portion standing to surface residue (affected and unaffected)	0	0	50	50	50	50	0
Portion surface cover left after time on	100	100	100	100	100	100	100
Roughness after time on (0 = not modeled)	0	0	0	0	0	0	0
Biomass removal post-forage clip height (0 = none)	0	0	0	0	0	0	0

† NA, this parameter is not used for the specified method, but the entire list is included for completeness.

hay, and 14.4 Mg ha^{-1} for the unharvested treatment. Annual forage harvest was 8.7 Mg ha^{-1} for the high grazing pressure, 6.6 Mg ha^{-1} under low grazing pressure, 9.9 Mg ha^{-1} for hay, and 0.0 for the unharvested treatment. The RUSLE2 plant growth model reduces growth in response to shading by standing residue (Dabney and Yoder, 2012), but the roles of surface residue on plant growth or forage availability are not considered. While under some conditions litter may improve forage production (Willms et al., 1993), heavy mulches may also suppress growth early in the growing season. This may be a reason why the unharvested bermudagrass treatment was predicted to be quite productive but didn't increase soil organic C as much as the grazing treatments (Franzluebbers and Stuedemann, 2009).

Ryegrass Pasture in Ireland

Dabney and Yoder (2012) developed a vegetation description (Table 6) for sod-forming perennial ryegrass (*Lolium perenne* L.) grown in the UK based on two studies, one involving alternative sheep grazing heights in Hillsborough in Northern Ireland (Chestnutt, 1992; Binnie and Chestnutt, 1994) and the other studying the effect of sheep grazing vs. silage harvest on subsequent stand morphology in Aberdeen, Scotland (Hepp et al., 1996). The resulting vegetation description varied between locations only in that the target NPP was set at 11.8 Mg ha^{-1} for Hillsborough and at 16 Mg ha^{-1} for Aberdeen, reflecting local climate and soil conditions. Here we compare the same vegetation description to a study by Carton et al. (1988a, 1988b) where ryegrass growing in Wexford, Ireland, was intensively grazed by cattle on up to four dates following silage removal in mid-August. The main thrust of the studies concerned the effect of autumn grazing termination dates (closing dates) in September, October, November, December, and an ungrazed control on the spring growth and tissue turnover of perennial ryegrass pastures. The sward was planted in August and grazed the following year until mid-June. It was then allowed to grow until mid-August, when it was cut for silage. After this, 100-m^2 plots were subjected to two grazing intensities (two or four 320-kg steers per plot grazing for 4 h) at approximately 4-wk intervals beginning in mid-September. The plots were subjected to either no grazing (C) or one (C1), two (C2), three (C3), or four (C4) grazing periods before mid-December, depending on the grazing termination dates. Plant growth was monitored before and after each grazing period and monthly thereafter until mid-April of the following year. The aboveground biomass was separated into leaf, stem, and dead material, but only the averages of the two stocking rates were reported.

Both the "lenient" and "severe" stocking rates in these studies were very high. Assuming 2.2% of body weight would be daily forage demand, the average of these stocking rates would equal a daily forage demand of 2100 kg ha^{-1} on the 0.01-ha plots, or about 179 AU ha^{-1}. Because the steers had fasted overnight and grazed for only 4 h, the actual forage demand was estimated by reducing the daily demand by two-thirds to 700 kg ha^{-1}. This was used as an input to the RUSLE2 model for each grazing period. With a potential NPP target of 12 Mg ha^{-1}, a climate description based on the average monthly temperature and rainfall for Clones, Ireland, and "grass forage" residue properties, forage removal operations using the "set rate, time on" option were developed that mimicked the grazing conditions of this study (Table 9). Matching the observed levels of standing herbage (Fig. 7) required the specification of considerable trampling of aboveground live and standing dead biomass during cattle grazing, which is reasonable considering the size of the plots and the stocking rates involved. Although

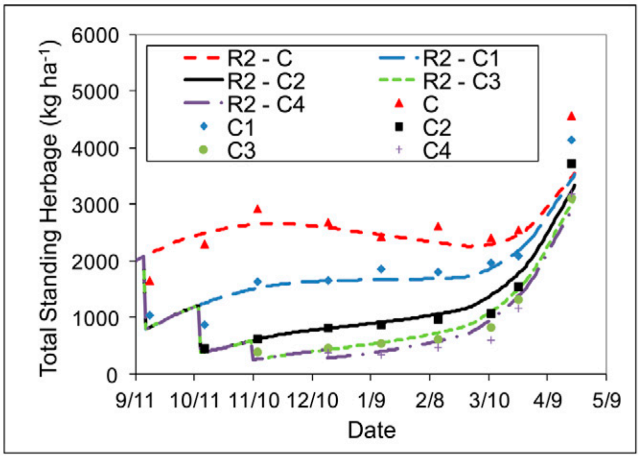

Fig. 7. Observed (points) and modeled (RUSLE2 [R2], lines) total aboveground ryegrass herbage in pastures in Ireland that were grazed by cattle 0 (C), 1 (C1), 2 (C2), 3 (C3), or 4 (C4) times at approximately monthly intervals after silage removal in mid-August (Carton et al., 1988a).

the forage demand was considered constant at 700 kg ha^{-1} during each grazing, RUSLE2 calculated a "shortfall" during each grazing period based on the "minimum height for full removal" limitation to harvest. Actual average forage removals reported by Carton et al. (1988a) for each grazing were: C1 = 614, C2 = 198, C3 = 107, and C4 = 46 kg ha^{-1}. The RUSLE2-simulated forage removals were similar: C1 = 640, C2 = 420, C3 = 140, and C4 = 36 kg ha^{-1} (Fig. 7).

Carton et al. (1988a) reported that after 4 h of "lenient" grazing, the amount of dead material in a perennial ryegrass sward increased (more dead material was created than consumed), while under "severe" grazing the amount of dead material declined and represented 18% of the biomass removed. Stem material was selectively avoided by grazing cattle to a greater extent than old leaves, with only 5 to 10% removed under either grazing intensity. Using the "nonselective" forage removal option, RUSLE2 predicted that standing dead residue represented the following fractions of forage consumed: C1 = 0.26, C2 = 0.30, C3 = 0.30, C4 = 0.0 kg kg^{-1}.

Runoff and Erosion Impacts

RUSLE2 estimates the runoff and erosion response to forage harvest and management through effects on the standing biomass, surface residue mass, and other associated variables. The full-year bahiagrass and bermudagrass studies allowed exploration of how forage management systems may affect RUSLE2-predicted runoff and erosion. The RUSLE2 profiles were developed using a common slope length of 30.5 m. Climate and soils descriptions were obtained from the official NRCS database (NRCS, 2012) to match the reported site conditions. The bahiagrass simulation was made using the Alachua County, Florida, climate and the "Pomona sand 70%" soil description. Pomona is a very deep, poorly or very poorly drained Lower Coastal Plain soil with hydrologic class D and erodibility (*K* factor) of 0.013 Mg h MJ^{-1} mm^{-1} in the database. The slope was assumed to be 2%, which is the upper end of the range associated with this soil. The bermudagrass simulation was made using the Oconee County, Georgia, climate and the "Madison sandy loam 100%" soil description. Madison is a very deep, well drained upland soil that has hydraulic class B and erodibility of 0.032 Mg h MJ^{-1} mm^{-1} in the official database. The

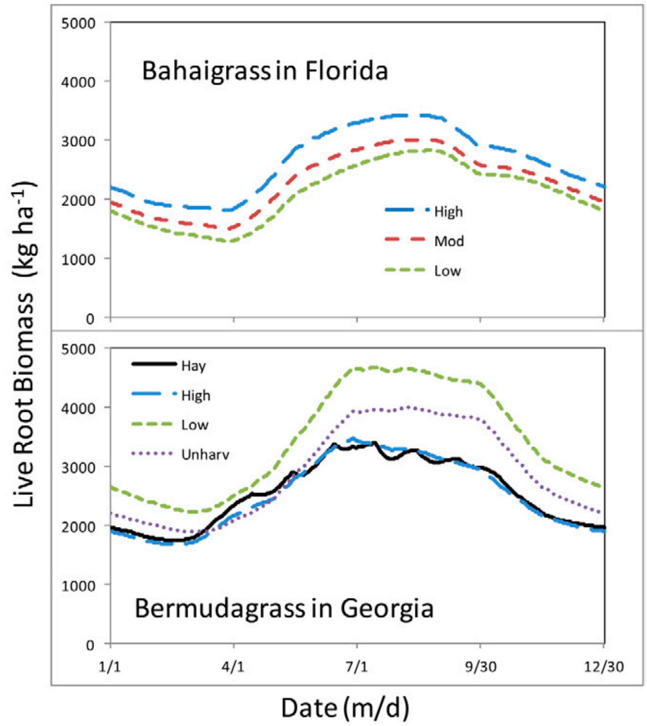

Fig. 8. The RUSLE2-predicted live root biomass (0–61-cm depth) corresponding to alternative bahiagrass (Fig. 4) and bermudagrass (Fig. 6) management systems.

slope was assumed to be 6%, which is the upper end of the range associated with this soil.

The resulting RUSLE2 predictions indicated that all management systems had erosion rates less than the "tolerable" rates (*T*) associated with each soil (Table 10). The bermudagrass hay system was the only profile with estimated erosion exceeding 1 Mg ha^{-1} yr^{-1}. Generally, runoff and erosion increased as forage removal increased. In the bermudagrass test, the hay treatment that removed 50% more forage resulted in more than a 10-fold increase in erosion and a 60% increase in runoff compared with the low grazing pressure treatment. The high grazing pressure treatment was intermediate, while the unharvested treatment had the lowest runoff and erosion estimates.

Runoff was predicted to be much higher from the poorly drained Pomona soil in Florida than from the steeper Madison soil in Georgia. Runoff and erosion variation among the bahiagrass management systems was small, with erosion varying by only a factor of about 2 and runoff varying <5% despite a threefold range of forage harvest. This probably resulted because both productivity and harvest removals were increased simultaneously in this study. The lack of difference in either runoff or erosion between the high and moderate management levels may reflect the increased root biomass (Fig. 8) that offset the effect of lower standing and surface residue biomass (Fig. 4) in the high management treatment. In contrast, in the bermudagrass study, all treatments received the same rate of fertilization, so the high grazing pressure and hay treatments had greater harvest removals but not greater productivity, so that the low grazing pressure treatment had the highest RUSLE2-predicted root biomass levels (Fig. 8).

Based on runoff and erosion amounts, the predicted average sediment concentration from the bahiagrass was 38 to 45 g m^{-3}, whereas from the bermudagrass site the estimated average

Table 10. The RUSLE2-predicted average annual erosion, runoff, and forage harvest for bahiagrass pasture in Florida with three levels of management (Dubeux et al., 2006a, 2006b) and bermudagrass grown in Georgia under four management systems (Franzluebbers et al., 2004).

Management	Erosion	Runoff	Forage harvest
	Mg ha^{-1} yr^{-1}	mm yr^{-1}	Mg ha^{-1} yr^{-1}
		Bahiagrass in Florida†	
Low intensity pasture	0.24	612	2.7
Moderate intensity pasture	0.58	637	5.3
High intensity pasture	0.58	636	7.9
		Bermudagrass in Georgia‡	
Low grazing pressure	0.14	158	6.6
High grazing pressure	0.88	221	8.7
Hay harvest every 28 d	1.75	252	9.9
Unharvested	0.03	143	0.0

† Profile properties: Alachua County, Florida, climate (1332 mm precipitation yr^{-1}); Pomona sand soil (hydraulic class D, erodibility [K] = 0.013 Mg h MJ^{-1} mm^{-1}, and tolerable soil loss rate [T] = 11 Mg ha^{-1} yr^{-1}); 30.5 m long, 2% steepness slope.
‡ Profile properties: Oconee County, Georgia, climate (1260 mm precipitation yr^{-1}); Madison sandy loam soil (hydraulic class C, K = 0.032 Mg h MJ^{-1} mm^{-1}, T = 9 Mg ha^{-1} yr^{-1}); 30.5 m long, 6% steepness slope.

sediment concentrations were 22 g m^{-3} for the unharvested, 89 g m^{-3} for low grazing pressure, 400 g m^{-3} for high grazing pressure, and 700 g m^{-3} for hay harvest treatments. Peak rates of runoff and erosion occurred during the winter months at the bermudagrass site but during the summer at the bahiagrass site (data not shown).

DISCUSSION

Management descriptions involving perennial vegetation are much simpler to develop using the new technology than using previous RUSLE2 vegetation descriptions because a single description can be used for growth that may span several years and because the new descriptions are quantified using expected harvest information (amounts and timing) better known to conservationists than the formerly required canopy and root growth pattern inputs.

The many options within the forage description and the forage removal process make it possible to achieve similar outcomes through alternative parameter combinations. Usually available data are not sufficient to distinguish among these alternatives. For example, in the ryegrass example heavy stocking rates where animals are forced to walk on forage in small plots probably resulted in some degree of trampling of live and especially standing dead forage, increasing the surface litter at the expense of standing herbage. However, no data are available to separate the various pathways that have been recognized by grazing lands specialists and incorporated into the "perennial biomass and current standing residue removal" process. Forage could be directly converted into surface residue or into standing dead residue that is subsequently flattened. Because the same result can be obtained through alternative combinations of process options, it cannot be said that the process option set selected is "correct" because the system is overdetermined.

Nevertheless, if a selected parameter set is logical and leads to results that mimic observations, then the vegetation and management descriptions will be useful for the main purpose of RUSLE2, which is to predict appropriate levels of canopy and residue biomass and therefore robust estimates of runoff and erosion for conservation planning. In the ryegrass example, the input variable set selected (Table 9) included specifying the grazing animal type as cattle with a 51-mm herbage height for full forage removal, which exponentially decreased removal with decreasing height below 51 mm, asymptotically approaching zero removal at a forage height of 25% of that value (Dabney and Yoder, 2012). This selection resulted in herbage levels, forage harvest amounts, and demand shortfalls that were similar to the reported values. This simultaneous match of multiple state variables and rates offers a degree of validation. Similarly, in the bahiagrass pasture study, altering the target NPP and forage harvest scheme allowed RUSLE2 to simultaneously mimic not only forage harvest but also residue creation rates. In the bermudagrass example, the target NPP was lowered under more intense grazing pressure to match forage harvest and residue biomass creation patterns. This shift is consistent with the reported development of bare areas, greater winter weed growth, and encroachment of common bermudagrass in the late summer (Franzluebbers et al., 2004). RUSLE2 cannot predict such state transitions; however, if such transitions are known to occur or can be predicted with more sophisticated modeling systems, RUSLE2 can estimate the impacts of such transitions on runoff and soil erosion. The RUSLE2-predicted soil erosion for the bahiagrass and bermudagrass systems were all found to be lower than the "tolerable" soil loss value for the soils involved, and all were <1 Mg ha^{-1} yr^{-1} except the bermudagrass hay harvest system that involved monthly cutting at a 5-cm height with a vacuum mower. The predicted pasture erosion rates were similar to those reported by Owens et al. (1989), where sediment yields from unimproved pasture in Ohio varied from 0.2 Mg ha^{-1} yr^{-1} for ungrazed management, to 1.2 Mg ha^{-1} yr^{-1} for summer-only grazing, to 2.1 Mg ha^{-1} yr^{-1} for all-year grazing including winter hay feeding, suggesting that the RUSLE2 predictions are the right order of magnitude and the responses to alternative management are in the correct directions and are suitable for conservation planning.

The new approach has been validated against the data sets readily available in the literature, but those studies were designed to address issues other than RUSLE2 vegetation and harvest effects and erosion estimates, so reports were often incomplete or required some interpretation. The new RUSLE2 approach could be best validated by several long-term studies of forage growth and harvest for different locations and climates with various types of vegetation and multiple harvest schemes. To be most applicable to validating RUSLE2, data sets should include seasonal forage harvest rates, periodic measurements of live and dead standing and surface biomass, and event records of rainfall depth and intensity, runoff, and erosion. It is difficult to define the model sensitivity to specific parameters on which such validation studies should place the most effort because this varies tremendously depending on the situation. For example, if there is not much surface cover, the predicted erosion rates will be very sensitive to the death of vegetation and the subsequent addition of more cover, while if substantial cover already exists, erosion rates will be insensitive to these additions.

RUSLE2 estimated up to 60% variation in predicted runoff among the bermudagrass systems modeled, with the hay system having the largest runoff value. Other studies have found that grazing tends to increase runoff relative to hay management (Van Keuren et al., 1979; Owens et al., 1983). RUSLE2 internally estimates a curve number (CN) used to calculate runoff (Dabney et al., 2011), responding to management effects by considering surface roughness and above- and belowground biomass levels. The current algorithms do not include a transitory compaction effect that could increase the CN in response to heavy grazing beyond its influence on biomass levels (Elliott et al., 2002; Pietola et al., 2005).

Combined with the underlying crop growth model (Dabney and Yoder, 2012), the options available in the new RUSLE2 "perennial biomass and current standing residue removal" process provide great flexibility in describing perennial vegetation management systems and predicting the effects of management alternatives on runoff and soil erosion. While year-to-year variability associated with changing weather is not considered, the new RUSLE2 technology does predict how management will affect residue creation—and thus runoff and erosion—throughout the year and through all years of multiyear rotations.

SUMMARY AND CONCLUSIONS

A new perennial vegetation harvest process was implemented in RUSLE2 that interacts with and controls the new perennial vegetation model described by Dabney and Yoder (2012). The new biomass removal process has an extensive set of options that allows the description of a wide variety of management systems. Information related to biomass removal may be specified at three levels: within the vegetation wizard to facilitate development of vegetation descriptions, in operation descriptions where default properties can be specified and stored as a named set, and within management descriptions that are used in profiles to calculate runoff and erosion.

The new forage removal process was illustrated by comparing observations with predictions for systems involving bahiagrass, bermudagrass, and ryegrass. In each example, a single vegetation description was used and stocking rates were set to match experimental treatment conditions. Net primary productivity was adjusted so that forage harvest, standing herbage, and residue creation were simultaneously tracked. In the bermudagrass example, the decomposition coefficient of unharvested treatment residues had to be lowered to match observations, reflecting qualitative differences related to residue particle size and composition. In the bahiagrass example, the RUSLE2-calculated "age" of the harvested forage was well correlated with IVDOM across low, moderate, and high levels of management intensity, suggesting that it may be a useful forage quality indicator. In the ryegrass example, forage harvest and shortfalls were correctly predicted, validating the forage height limits to grazing implemented in RUSLE2 based on expert opinion.

The new biomass removal process and vegetation model technology make it much easier for conservationists to adequately describe land management systems that include perennial vegetation. RUSLE2 can now dynamically adjust the amount and timing of residue creation resulting from alternative forage harvest schemes based on a single vegetation description. The NRCS has developed an extensive set of vegetation, operation, and management descriptions that will be included in updates to their official database that were scheduled to be released, along with a new version of RUSLE2, sometime during the 2013 calendar year. For actual NRCS implementation, it is not envisioned that NRCS field office users would be developing vegetation descriptions, but that they would rather be using vegetation and management scheme descriptions defined by higher level users and stored in the database. The field office users would simply modify overall yields and perhaps build multiyear rotations as needed to describe their situations. Others interested in implementing this new RUSLE2 approach may be interested in linking it to their own modeling or management efforts through use of the RUSLE2 dynamic-link library (dll), which allows other computer programs to have access to input values into RUSLE2 and to get answers in return. This allows almost all of the capability of the RUSLE2 interface but can be accessed from other programs.

When adopted, this new technology will allow simpler procedures to describe management systems and provide more reliable estimates of runoff, erosion, and sediment delivery from pasture and hay lands for conservation planning throughout the United States.

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