Modelling Aeolian Agro-Environmental Landscape Dynamics

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ABSTRACT

Land surfaces where vegetation and aeolian sediment transport interact are complex systems that evolve through non-linear relationships between physical geomorphic processes and biological plant growth and response. Modelling these systems can be challenging, particularly over longer periods, because of the cumulative effects of dynamic environmental parameters and antecedent conditions playing out over various spatial and temporal scales. Current modelling approaches range from small-scale reductionist quantification, for predicting soil erosion by wind over agricultural fields for example, to large-scale self-organisation models, for simulating 3D dune field evolution for example. This paper reflects on the similarities, contrasts, and gradations between the various modelling strategies that have been developed over the last few decades, as well as current innovations and progress. The paper will review various kinds of practical considerations – such as technical and numerical issues, parameterisation problems, and balancing the scales and representation of different types of processes – as well as fundamental questions of calibration and validation, application, and science potential.

INTRODUCTION

Landscapes and environments where vegetation and aeolian sediment transport interact are complex systems that involve non-linear relationships between physical geomorphic processes and biological plant dynamics. Not only is the basic relationship between wind forcing (quantified as a wind speed or a shear velocity) and the resulting sediment transport flux fundamentally non-linear (usually modelled as a cubic function, based on dimensional analysis arguments), but the impacts and response of vegetation elements, soils, plants, and crops is inherently complex and involves a range of feedback mechanisms between a large number of constituent elements in the agro-environmental system. All these components are furthermore subject to anthropogenic manipulation and modification through a vast range of land-use and management interventions, particularly in the context of agricultural practices. The kinds of environments and processes that may be considered in this context then cover a wide range, including such landscapes as deserts, semi-arid regions, agricultural fields in a range of climates, beaches, and coastal dune fields, and such processes as soil erosion by wind, dust emission, surface deflation, and dune formation. All of these systems include forms and processes that span across a wide range of spatial and temporal scales, from the grain-scale interactions between wind turbulence, sediments (clay, silt, sand), and plant elements, to regional (spatial) scales of coastal & continental dune fields, agricultural regions, and global atmospheric dust transport, as well as decadal to centennial (temporal) scales of wind climate, vegetation succession, and soil deflation. A comprehensive understanding of aeolian agro-environmental systems therefore requires simultaneous integration along two challenging fronts: the integration of physical and biological processes, and the integration along spatial and temporal scales.

While we know quite a lot about the fundamental physics of sediment transport by wind and its integration to bare-sand dune development and evolution, the biology and soil aspects of these systems are still poorly understood and constrained. The formative controls on desert sand dune types (barchan, transverse, linear, star) are, for example, straightforwardly represented in the well-known Wasson & Hyde (1983) diagram, but the development of a similar phase-diagram for dune forms that involve vegetation is hampered by the complexities and challenges of quantifying and parameterising biological plant properties and variables on a footing that is exchangeable with the (much simpler) abiotic variables in the system (Baas and Nield, 2007; Baas and Nield, 2010). Furthermore, empirical (field) data that are required to fully quantify and represent the biological and soil controls are largely lacking, or are only available from simplified laboratory and wind tunnel studies that investigate, for example, the airflow and sand transport around individual plant elements (e.g. Leenders et al., 2011; Wolfe and Nickling, 1993) or the response of specific plant species to sand burial response (e.g. Yuan et al., 1993).

Computer simulation modelling can provide a powerful avenue for advancing and applying our understanding of agro-environmental systems. Models can integrate and reflect our current understanding of the many processes and conditions operating in this environment, including the physics of wind-blown sand transport, the dynamics of airflow over topography, the surface conditions, climatic controls, and vegetation effects, over a range of multiple temporal and spatial scales. Integrating this understanding into quantitative models is particularly useful because it gives us the capacity to transcend the long time-scales that are often involved with the development and evolution of large aeolian landscapes, as well as allowing us to consider places that are inhospitable or cannot be easily monitored directly. Models can be applied to specific local situations to help with inferring historical landscape development (e.g.: Levin et al., 2009; Pelletier et al., 2009), with exploring (non-) equilibrium conditions and temporal lags between landforms and local wind regimes (e.g. Elbelrhiti et al., 2005), and with projecting potential future landscape development scenarios (e.g. Baas et al., 2010; Nield and Baas, 2008a). Modelling can be a powerful avenue for informing stake-holders and resource management in agricultural settings, to evaluate interventions and to predict potential soil losses under changes in land-use or climate, and long-term models can furthermore integrate the cumulative effects of low-intensity and difficult-to-measure sediment transport, deflation, and deposition over large areas (Fryrear et al., 1998; Hagen, 1991; Riksen and Visser, 2008; Visser et al., 2005a).

This short paper aims to provide some reflections on various modeling approaches, taking into account the historical context of modeling aeolian landscape dynamics, with an emphasis on vegetation and biological controls, and contemporary challenges and innovations, while considering the implications of and requirements for some general good modelling practices.

THE MODELLING SPECTRUM

Reflecting on model development in agricultural and environmental research & application it may be fruitful to consider the variety of attributes, styles, and types of models in general. One way of exploring innovations is to consider modelling characteristics along dimensions of contrast (e.g. Haggett and Chorley, 1967; Slingerland and Kump, 2011), including:

- static ↔ dynamic: models that represent 'equilibrium' features or structures as opposed to models that focus on processes and changes over time,
- descriptive ↔ normative: models that are concerned with a stylistic or simplified description of reality as opposed to models that attempt to predict outcomes under certain conditions,
- stochastic ↔ deterministic: models that represent aspects of a geomorphic system in terms of probabilities and statistics as opposed to models that quantify specific precise values,
- process-based ↔ form-based: models that simulate physical processes that are thought to operate in reality as opposed to models that represent shapes and forms found in the landscape,
- forward ↔ inverse : models that attempt to predict a final or future state of an environmental system as opposed to models that aim to determine past initial or boundary conditions based on a current state,
- black box ↔ white box: models that use 'invisible' or untraceable internal procedures (often involving advanced statistical methods) as opposed to models where all processes and relationships are transparent and precisely specified,
- inductive ↔ deductive: models that represent a system by generalising and categorizing from empirical findings as opposed to models that assume a theory or framework to simulate consequent forms and processes,

The main interest of considering dichotomies like these is for the practising modeller to reflect on their own model choices and strategies, to compare and contrast with other types and to elicit alternative and novel ways of thinking about one's own modelling approach and context that can help spur new ideas, opportunities, and extensions.

Another way of exploring model innovations is to consider more fundamental differences in terms of the underlying philosophy or approach of representation (Malamud and Baas, 2012), including: i) traditional physically-based computer models, ii) cellular-automata models, and iii) statistical/empirical models of observed or simulated data.

Traditional physically-based computer models simulate systems within a reductionist-deterministic context of quantifying small-scale physical processes, based on exact empirical or theoretical relationships (equations). These models can either represent point-source bulk properties for the system as a whole, or they can be implemented within a spatially explicit and discretized domain or grid (2D or 3D), and present temporal evolution in discrete time steps. The detailed representation of multiple physical processes requires a large number of parameters, coefficients, and calculation steps and these models can therefore be 'expensive' to run on computers. Examples of such models in agro-environmental research and application include the Wind Erosion Prediction System (WEPS) for wind-driven soil erosion on agricultural fields (Hagen, 1991), Simulation of Aeolian Foredune Evolution (SAFE) for coastal dunes (Van Dijk et al., 1999), and various advanced coupled airflow-sand transport models (e.g. Andreotti et al., 2002a).

Cellular Automaton (CA) models also involve discretized spatial domains and step-wise time-evolution, but simulate physical processes as simplified rules of interactions between neighbouring cells on a grid, that self-organise toward emerging landscape forms and behaviours. These models usually rely on the intensive repetition of a simple algorithm that involves a restricted set of parameters and can therefore be 'cheaper' to run on a PC. Examples include the Werner (1995) model of bare-sand dunes, and the Discrete ECogeomorphic Aeolian Landscape model (DECAL) for vegetated dunes (Baas, 2002; Nield and Baas, 2008b).

Statistical or empirical models quantify systems and processes as a structure derived from analysing measured data sets directly, usually in the form of simple statistical relationships, such as regressions and curve fitting, or as variables and factors that are presented by coefficients and parameters derived from categorised tables and empirically established values. Some of the predictive soil erosion equations rely on such empirically derived classifications and relationships, although they are usually implemented within a rudimentary methodology of recognising key physical components/processes, involving multiplication of different factors. Examples include the Universal Soil Loss Equation (USLE: Wischmeier and Smith, 1978), the Wind Erosion Equation (WEQ: Woodruff and Siddoway, 1965), and the Revised Wind Erosion Equations (RWEQ: Fryrear et al., 2000; Fryrear et al., 1998).

Finally, the purpose and application of the modelling effort can also have significant implications on the choice of simulation strategy and model structure, with respect to potential end-user needs and limitations, or the production of new understanding and the exploration of science questions. Some models are explicitly designed to be used by practitioners and land-use stake holders, requiring user-friendly menu & output interfaces and carefully defined data inputs & parameters. Other modelling efforts are aimed at exploring fundamental science questions regarding the interactions between physical processes and forms, requiring explicit representations of spatial and temporal processes and often tailored toward either artificial simulation experiments, or to site-specific set-ups for empirical testing.

MODEL DEVELOPMENT IN AGRO-ENVIRONMENTAL RESEARCH & APPLICATION

The history of modelling aeolian landscape dynamics and wind erosion has been a progression of representation in increasing number of spatial dimensions, from point (1D) models of dunefield activity and bulk estimates of erosion rates on agricultural fields, through to fully three-dimensional time-evolution of geomorphology and sediment transport.

Point-source or unit models

Dune mobility models (1D), in the form of simple equations, have been some of the earliest quantitative representations of aeolian systems, contrasting the key forcing agent of the sediment transporting capacity of the local wind regime with the extent of vegetation coverage as the main limiting factor on the yearly to decadal time-scales of interest. These two facets have been juxtaposed using climatic variables in various ways to define mobility indices that predict the degree of dune activity, with the vegetation factor usually estimated as a function of soil moisture availability. Chepil et al. (1962), for example, proposed a 'wind erosion factor', calculated as the cube of a local mean annual wind speed divided by Thornthwaite's climatic moisture index (the difference between annual precipitation and evapotranspiration). Another mobility index was proposed by Wasson (1984) based on the percentage of days with sand-moving winds and the ratio of annual potential evapo-transpiration to annual precipitation. The approach of quantifying the forcing by a time percentage of sand-moving winds was also adopted in the most widely known dune mobility index, the 'M'-index developed by Lancaster (1988). More recent advances in predicting dune mobility include the hysteresis model of Tsoar (2005) and Yizhaq et al. (2007; 2009), describing the differing progression rates of stabilisation versus reactivation of coastal dunefields, and the systems-framework model of Hugenholtz and Wolfe (2005a) that considers climatic perturbations and response lags for continental (inland) dunefields (Hugenholtz and Wolfe, 2005b; Hugenholtz et al., 2009). Modelling of dune field activation and stabilisation remains an important area of research, as sedimentary dune deposits and their datings are frequently used to infer records of aeolian activity and associated palaeo-climatologies.

Another important family of aeolian models has matured in the agricultural context of soil erosion by wind, starting with the wind erosion equations developed at the USDA Agricultural Research Service. The original Wind Erosion Equation (WEQ) developed by Woodruff and Siddoway (1965) is similar in approach as the Universal Soil Loss Equation, as a multiplication of a number of factors and coefficients to arrive at a gross annual estimation of soil loss for an agricultural field as a whole. The factors include soil erodibility, soil ridge roughness, climatic forcings and controls, and field length (fetch), each of which is derived from more detailed individual components such as wind velocities, soil moisture, soil crusts, quantity-, kind-, and orientation of vegetative cover (crops), etc., and need to be combined partly via graphical methods (using nomograms). This predominantly empirical model was later adapted and extended by Fryrear et al. (2000; 1998) into the Revised Wind Erosion Equation (RWEQ) to change from annually averaged soil estimation to a shorter timescale of individual erosion events, as well as to include more crop and soil factors. These empirical wind erosion equations were superseded in the 1990s by a more reductionist process-based model, the Wind Erosion Prediction System (Hagen, 1991). This model simulates the physical processes of wind-blown soil erosion, its interaction with roughness elements and wind-breaks, and the various surface controls of soils, hydrology, and agricultural practices, on a relatively short timescale of daily time steps. Many of the processes are quantified as physically meaningful relationships and functions at a detailed level, while other factors, particularly those related to crops, tillage and soil effects, are empirically derived. As with the wind erosion equations, WEPS simulates bulk soil erosion for agricultural fields as single units, and has been tested and compared to field measurements in various studies (Hagen, 2004; Van Pelt and Zobeck, 2004; Zobeck et al., 2003). Although variable wind directions and field boundary controls such as windbreaks are included in the model, internal patterns of erosion, deposition and topographic development within the modelled domain are not considered and the model is not spatially explicit as such.

Transect models

Transect models (2D) are usually based on the Exner (continuity) equation for surface evolution resulting from sediment transport, relating erosion or deposition at a point to the local gradient in transport flux (Exner, 1920; Exner, 1925; Paola and Voller, 2005). Models that simulate hillslope profile evolution resulting from soil erosion by water, e.g. WEPP (Flanagan et al., 2007; Nearing et al., 1989), assume a sediment transport rate proportional to the local surface slope. In the case of aeolian systems, however, sediment transport is governed by the forcing of the wind and the strategy of surface evolution modelling heavily depends on the dynamic simulation (or not) of the airflow (shear stress) over the surface.

Numerical modelling of the evolution of a transect profile has been particularly prevalent in the coastal environment context, starting with simulation strategies that assume a uniform wind forcing along the whole transect or do not incorporate the dynamics of the airflow directly. Jungerius (1984), for example, implemented a basic quantitative algorithm of blowout development that deflates and redistributes sand between cellular compartments subject to some simple rules, to simulate the upwind lengthening of a blowout and the development of a secondary dune downwind. A more physically-based transect model was constructed by Castel (1988) for simulating profile development in drift sand areas. This model calculates the deflation at 3 metre intervals along a transect using Bagnold's transport formula, constrained by the local vegetation height, and determines the amount to be deposited at the next (downwind) location taking into account the surface slope.

These two earlier models do not strictly follow the Exner equation, as they quantify erosion and deposition using partly qualitative rules and constraints. The AEOLUS-II model developed by Namikas and Sherman (1998), however, does calculate aeolian sedimentation/deflation along a transect as a result of (negative/positive) changes in transport flux between one grid-point and the next. This comprehensive computer model includes a large number of selection and input options, such as different sand transport formulae, soil moisture and slope effects, and the use of either a fixed wind forcing or a map of shear velocities along the topographic profile.

The transect models discussed so-far require a uniform or user-defined wind forcing along the profile and do not dynamically evaluate the near-surface airflow and shear velocity over the developing topography (in the case of dunes) and/or surface roughness (in the case of vegetation and crop patterns). Progress in simulating the full surface evolution has therefore required the development of coupled airflow-sand transport models that have relied on fluid dynamics theory.

The Navier-Stokes equations for turbulent fluid flows cannot be solved analytically in closed form, and so for the modelling of airflow over dunes approximations or simplified forms need to be implemented instead. The most widely used approach in dune modelling was developed by Jackson and Hunt (1975) for airflow over a low hill, later updated and revised in Hunt et al. (1988). This analytical model makes some assumptions about the structure and behaviour of the near-surface layer to predict a wind speed-up ratio as a function of height, relative to an upwind reference velocity (a detailed summary can be found in (Nickling and McKenna-Neuman, 1999). The model is limited to low symmetrical hills and was used by Weng et al. (1991) to calculate the resultant sand transport flux over an idealised barchan dune. The model also forms the basis for the more recent quasi-3D simulation models discussed further below. A close alternative to the Jackson and Hunt model was developed by Zeman and Jensen (1987), following a similar simplification of the airflow problem. Their analysis includes the effects of streamline curvature, however, and can therefore handle steeper topographies. Jensen and Zeman (1985) implemented their model with a Bagnold sand transport equation component to successfully simulate the development of 2D transect dune shapes (Zeman and Jensen, 1988).

The Zeman and Jensen model has subsequently formed the basis for the implementation of a 2D transect model for airflow over transverse dune shapes by Van Boxel et al. (1999), which was then combined with a Kawamura (1951) sand transport equation component to produce the 'SAFE' model (Simulation of Aeolian Foredune Evolution) for application to coastal dune environments by Van Dijk et al. (1999) as well as modelling the effects of beach nourishment on profile development (Van der Wal, 2000). More importantly, SAFE was subsequently expanded to include the effects of vegetation on airflow and sand transport, based on the Raupach et al. (1993) roughness approach, and has subsequently been used to simulate the effects of artificial reed bundle plantings on the back-beach for inducing and promoting sand accretion at the toe of a foredune (Arens et al., 2001).

Three-dimensional models

Following the quantitative revolution of the late 1960s and early 1970s a number of studies explored the numerical simulation of sediment transport over shaped surfaces and the modelling of the development of dunes and general bedforms, starting with Howard et al. (1978), who applied a sediment continuity model over a digital elevation model of an existing (measured) barchan dune. Howard and Walmsley (1985) followed this work by applying an analytical airflow model similar to Jackson and Hunt (1975) to simulate topographic evolution starting from a circular sinusoidal pile of sand toward a barchanoid shape. The full evolution from a conical pile to a barchan dune was successfully achieved by Wipperman and Gross (1986), using a meso-scale numerical flow simulation model, developed for meteorological applications, combined with a Lettau and Lettau (1978) sand transport equation.

After a quiet period in the 1990s, the reductionist physically-based modelling of coupled airflow-sand transport dynamics and the resulting surface evolution has seen major advancement in the recent decade. The modelling strands developed by Andreotti and colleagues (Andreotti et al., 2002a; Andreotti et al., 2002b; Hersen et al., 2004) as well as Herrmann and colleagues (Herrmann, 2002; Kroy et al., 2002; Sauermann et al., 2001) consider the saltation flux and the feedbacks with flow forcing and local topography in a continuum model of a transport layer over a developing profile, which is driven by an airflow model derived from the Hunt et al. (1988) analysis. Both strands simplify the problem of the separation flow zone behind a dune slip face by excluding it from the calculation domain along a polynomial envelope extending from the brink to the re-attachment point. Both model families also operate rather on a quasi-3D basis, as in practice they simulate airflow and sand transport along a series of independently modelled parallel transects that are then tied together into a 3D domain through a lateral stress component (Schwammle and Herrmann, 2005) or a lateral reptation flux (Hersen, 2004). The coupled airflow-sand transport model has also been extended to include the effects of roughness elements like vegetation, as well as their burial during deposition, to simulate transitions from barchan dunes to parabolic dunes (Duran and Herrmann, 2006; Duran et al., 2008)

During the 1990s the modelling of aeolian landscapes turned away from detailed reductionist analysis of airflow forcing and sand transport response, to explore instead the capabilities of simple cellular automata (CA) to simulate the non-linear dynamics of dune field development as emerging self-organising patterns. The prototypical model of this approach was developed by Werner (1995), using an algorithm that repetitively moves discrete slabs of sand across a cellular lattice grid, subject to localised erosion and deposition probabilities, including a 'shadow zone' of no-transport in the lee of a sand heap, and enforcing an angle-of-repose through avalanching. Without modelling any reductionist airflow and sand transport dynamics, this simple model is capable of generating realistic barchans, transverse dunes and linear dunes through the self-organization of accumulating and migrating sand heaps, starting from flat surfaces. This algorithm can replicate the Wasson and Hyde (1983) phase diagram for desert dune types (Bishop et al., 2002), and has served as a tool for analysing and conceptualising the fundamental principles of bedform pattern self-organisation (Kocurek et al., 2009; Werner, 1999; Werner and Kocurek, 1999). It has been further refined to simulate the local acceleration of wind over the stoss slope of a dune by Momiji et al. (2000) by incorporating a simple wind speed-up rule, and has been extended by Eastwood et al. (2011) with variable input (source) and output (sink) boundaries to simulate the controls of sediment supply and transport capacity on dune field pattern evolution.

The Werner algorithm was expanded by Baas (1996; 2002) to include vegetation and its effects and feedbacks with the sand transport process into the so-called DECAL model (a similar adaptation was also explored by Nishimori and Tanaka, 2001). The impact of plants on sand transport is simulated by changing local erosion and deposition probabilities in relation to the amount of vegetation present on a cell, and the effect of deposition (burial) or erosion on the plants is simulated by a 'growth function' that annually updates local growth or decline of the plants. The model can include multiple vegetation types and is capable of successfully simulating the development of parabolic dunes – in particular the formation of vegetated trailing arms – as well as nebkhas (Baas and Nield, 2007; Nield and Baas, 2008b). An incorporation of vegetation similar to DECAL was recently applied by Pelletier et al. (2009) to simulate the historical evolution of a real vegetated dune ridge situated on the North Carolina coast.

In the field of agricultural wind erosion modelling the recent decade has seen a novel expansion and implementation of the WEPS approach to a spatially explicit 3D lattice domain by Visser et al. (2005b). The original WEPS model treats agricultural fields as single units and provides only bulk erosion estimates. Visser rewrote the erosion sub-model of WEPS into the map-based modelling application of PCRaster (Wesseling et al., 1996) so that all the surface factors and parameters can be treated as defined spatial variables, allowing simulation of the within-field patterns and dynamics of erosion and deposition responding to locally varying soil and vegetation conditions. This model has been applied to soil erosion in Sahelian environments (Visser et al., 2005a; Visser et al., 2005b) as well as tillage practices in drift-sand areas (Riksen and Visser, 2008), and was also further integrated with a rainfall erosion model to assess the potential total soil nutrient losses from agricultural fields in semi-arid regions (Visser et al., 2005c). This spatially explicit version of WEPS is multi-directional, but simulates the wind forcing (shear stress) as a uniform driver over the entirety of the grid and without surface topography feedback, similar to the approach of the CA models discussed above.

COMPARISON AND INNOVATION

The last few decades have seen great progress in modelling capacity to the point that we can now convincingly simulate the development of dune fields with a high resolution, both through a reductionist approach as well as using self-organising cellular automaton algorithms, as well as predicting wind-born soil losses on agricultural fields over a range of scales and for a multitude of management situations and conditions, using highly sophisticated and user-friendly software. Recent and future innovations in agro-environmental modelling come from both: 1) combining across the interface of disciplinary boundaries, such as the DECAL integration of biological plant dynamics into previous bare-sand (physics-based) algorithms, and 2) combining or extending different types of models to achieve new syntheses, such as the implementation of the WEPS approach into a spatially explicit 3D simulation domain.

An excellent contemporary example of both aspects of innovation is the modelling work being developed at the University of Wageningen by an inter-disciplinary group that combines different research disciplines and environmental spheres into a single integrated model, based on a fundamental CA approach, to simulate (three-dimensionally) the initiation and development of foredunes in the coastal zone (De Groot, 2012). This work has the basic DECAL algorithm at its root, but then greatly expands the vegetation component by replacing the original rudimentary approach with a much more sophisticated (1D) nutrient recycling model (NUCOM) that governs soil resources and plant growth dynamics, based on a suite of physical parameters and coefficients of plant physiology (Berendse, 1988). The model is further extended across disciplinary boundaries by also including a significant sea wave action (hydraulic) component to interact with the beach profile, topographic development, and colonizing plants. Another branch of this project includes a cross-breeding between WEPS and DECAL, combining the detailed surface control factors of the former with the self-organising stochastic movement of discrete slabs of the latter, in a modelling framework that is an amalgamation of a reductionist process-based approach with a CA philosophy.

In this context it is important to recognise that reductionist airflow-sand transport models and self-organising cellular automata are not mutually incompatible and should rather be seen as end-members of a spectrum of different degrees of process simulation and choices about relevant mechanisms to incorporate. CA models have, for example, been adapted to include more explicit airflow effects, such as the wind speed-up over the stoss slope, while the exclusion of the separation flow behind a dune along a boundary envelope in the coupled airflow-sand transport models is a simplification that is very similar to the shadow-zone rule in the CA algorithms. Similarly, there is a gradual range of different degrees of detail with regard to the representation of vegetation and soil components in the agro-environmental models, from the very simplistic vegetation growth function of DECAL, through the more elaborate parameterisation of soil moisture, texture, crust, tillage, and crop characteristics in WEPS, to the sophisticated calculation of nutrient cycling between soil horizons and plants of NUCOM. Conversely, the treatment of vegetation burial and response is very similar between the reductionist airflow-sand transport modelling of, for example, SAFE (Arens et al., 2001) and Duran et al. (2008), as compared with CA algorithms such as DECAL.

Reductionist and CA modelling strategies each have their own advantages and disadvantages with regards to the ultimate goal of the effort, the available computational resources, and the type and extent of empirical inputs and outputs that are required.

CHALLENGES AND GOOD MODELLING PRACTICES

Regardless of the type of modelling strategy being pursued, there are a number of methodological issues that should be considered. Malamud and Baas (2012) propose nine criteria for constructing and running geomorphic models, that are equally applicable to agro-environmental models in general. The first four recommendations concern the model construction phase, and include: 1) choose a type and character of model type or strategy that is appropriate for the project goal and suitable for the empirical data available, 2) maintain parsimony in the model, i.e. curtailing the number of processes and parameters to the minimum necessary (cf. ‘Occam’s Razor’), 3) apply dimensional analysis to reduce parameter freedom and to verify the integrity of variables and their units, and 4) conduct benchmark testing (run settings that should generate exactly predictable model outputs) to confirm the model is working as intended. When running a model five more practises should be considered: 5) sensitivity analysis to assess which processes and parameters influence results most (and should therefore be quantified most accurately), 6) calibration to adjust the model to real-world empirical applications, 7) model data exploration to identify trends and anomalies, 8) uncertainty assessment to quantify confidence limits around model predictions, and 9) considering alternative models, data and questions.

In the context of these recommended modelling practices the development of innovative aeolian agro-environmental models faces a number of specific challenges that are inter-linked.

First is the issue of transcending and integrating across different spatial and temporal scales and the associated question of the resolution of the model. Traditional reductionist process-based approaches, like the coupled airflow sand transport models, are of-course based on the idea of integrating small-scale physics into large scale landscapes, but this suffers from two limitations: 1) the integration of many inherently non-linear processes risks the manifestation of chaotic model behaviour and susceptibility to crippling numerical instabilities, rendering the reductionist approach powerless, and 2) scaling-up to larger domains increases the computational cost exponentially, restricting the practical implementation. Conversely, cellular automaton strategies embrace the emergent behaviour and self-organisation of large non-linear systems and are much 'cheaper' to run over large domains, but their fundamentally stochastic nature at the local scale precludes any site-specific and precise replication of empirical situations other than on a statistical basis. Meanwhile, explicitly empirical models, such as WEPS, may be practically implemented in real-world land-use problems, but their application is strictly confined within the boundaries of the observational data sets and restricted by the protocols that define the quantification of the small-scale processes. In many cases, the issue is not so much one of scale transition, but rather of properly harmonizing the spatial and temporal scales of representation of different aspects or components within the model of an agro-environmental system. This requires a consideration of model parsimony, sensitivity analysis, and uncertainty assessment, to ensure that some components are not overly detailed or excessively sophisticated in comparison with other aspects.

The issue of harmonizing the scales of model components is particularly relevant to the second challenge, the incorporation and balancing of the vegetation (biological) element, relative to the abiotic processes. The effects of vegetation on the aeolian sediment transport system are still relatively poorly understood, and in particular not well quantified with physically meaningful variables and parameters that can be integrated with the abiotic processes. This limits its modelling representation to very simplistic relationships, as in DECAL for example, or to purely empirically defined functions, such as the impact of roughness density (an essentially geometric property) on local wind forcing (Raupach et al., 1993; Raupach and Lu, 2004). Furthermore, the reciprocal impact of sediment transport, erosion, and deposition, on plants themselves is also poorly quantified. The effects of sand burial on typical foredune vegetation species such as marram grass have been, for example, only measured and quantified precisely in greenhouse pot experiments (e.g. Yuan et al., 1993) using single plants, whereas the effects on whole stands or patches in the field have not been monitored sufficiently adequately to enable thorough parameterising in simulation models. Furthermore, conceptual analysis of the differences between the Werner bare-sand dune algorithm and the DECAL vegetated dune model demonstrates the impact of incorporating plants. The linkage of a biotic component (vegetation) and the abiotic component (sand transport) suggests that the physiological properties of the vegetation, and thus how it is simulated, may impose a specific physical scaling to the resulting landscape (Baas and Nield, 2007), and balancing the scale and representation of the two aspects in a model is thus crucially important.

The third challenge for aeolian agro-environmental modelling is the issue of testing and evaluation of simulations relative to empirical field data, a challenge that is shared with modelling in Earth-sciences in general but which is exacerbated here by the inclusion of the biological vegetation aspects (see above). Not surprisingly, the more empirical models such as WEPS are better constrained in this context (Zobeck et al., 2003), as they are partially based on observational data to begin with, and since they are designed for practical use they are naturally more easily tested and evaluated against field measurements (as well attracting more opportunities and resources for evaluation). For CA models, meanwhile, the comparison of simulations against reality usually requires a statistical approach, but quantitative state variables or landscape metrics that integrate the characteristics and spatial relationships of vegetation and topography for comparison to real-world field sites are still underdeveloped (Baas and Nield, 2010). The most significant problem with testing and validation of agro-environmental models is perhaps the need for long-term monitoring over extensive field sites requiring a broad and diverse array of instrumentation that furthermore provides high-resolution measurements over a large spatial and temporal scale. Most of the effective work that is done by the wind in these systems is highly event driven, be it dust storms in semi-arid regions that induce heavy soil erosion on agricultural fields, to mid-latitude winter cyclones that drive sand transport on beaches and the development of new coastal foredunes. Measuring the cumulative effects of such events to compare with the long-term model simulations requires a significant investment in time and resources.

CONCLUDING REMARKS

This paper has reviewed various ways of thinking about the modelling of aeolian agro-environmental systems and some of the challenges, good practices, and on-going innovations. Regardless of whether a model is developed for the purpose of fundamental scientific exploration or for practical application by end-users, and regardless of the exact type, scale, or strategy that is pursued, the development and innovation of aeolian agro-environmental models requires a careful consideration and evaluation of the parameters and processes that are being simulated. What is often not stated explicitly in the literature, however, is that the very act of developing a model and the practical decisions that have to be researched along the way can lead to fundamental questions and significant insights. That is, many interesting scientific and practical advances arise *during* the model development (rather than from its outputs), and in this sense the journey is often more fruitful than the final destination.

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