Response to referees for "**Creative computing with Landlab: an open-source toolkit for building, coupling, and exploring two-dimensional numerical models of Earth-surface dynamics**", by Hobley et al.

Dear Simon,

Please find below a synthesis of our responses to all of the comments made by each of the reviewers/commenters: Schwanghart, Wickert, and Campforts. As directed in the submission letter, we have pasted their text into this document, then beneath it posted a reply and a quotation of any changes made as a consequence of that reply. In the case of the longer reviews from Wickert and Campforts, we have done this beneath each segment of their review. As then requested, we have also attached a full version of the manuscript to the end of this file, which tracks all changes made as part of this process (excepting minor formatting issues, and some faffing about with my reference manager). The version uploaded separately to the web interface is the final version with all changes accepted.

We hope that we have been able to address all of the reviewers' comments to both your and their satisfaction. Beyond this, we've also taken some time in particular to attempt to clean up the formatting of the references, which hopefully should now all meet ESurf standards. We also noticed an erroneous cite in one place (the attribution of one of the models in Fig. 1 should have been to Berger, not Ivanov) and also have replaced a reference to a conference proceeding by Adams et al. with a better citation to a GMD discussion article by the same authors. (I wanted to highlight these specifically, as the fact they were automated changes made my reference manager means they will not show up well in the tracked changes.)

Many thanks for taking the time to handle this manuscript, and also for having taken the time to look it over for yourself. We look forward to hearing from you in due course.

Dan Hobley (on behalf of the authors)

Response to W. Schwanghart

Comment:
I congratulate the authors to provide the community with Landlab and this accompanying paper. As the authors share their model as an entirely open software on GitHub, they adhere to the growing trend of open collaboration for scientific computing. This is great! This being said, I found it a bit surprising to find TopoToolbox and TecDEM referenced as closed source software (page 4, line 9), in line with ArcMap and Matlab. I agree that ArcMap and Matlab are closed and commercial software. Yet, the Matlab-based toolboxes TopoToolbox and TecDEM themselves are open software as their codes are open and could be run (although with major modifications) on platforms like Octave, which itself is open. I think that there is a smooth transition between fully open software such as Landlab which is based on Python, software such as TopoTool- box and TecDEM that exploit the increasing openness and interoperability of commer- cial and closed software such as ArcGIS and Matlab, and completely closed-source software. I encourage the authors to account for this slight but significant difference in principles of software development.

1st Reply:

Dear Wolfgang,
Your comments are well-taken. We will work harder in the forthcoming revision of the manuscript to emphasise the spectrum of accessibility of existing codes, particularly re Topotoolbox and TecDEM. The status of codes which themselves are open source but nonetheless exist as extensions to major pieces of closed-source software is interesting, as you point out, and certainly worthy of emphasis here. We'll ensure the revision adds this nuance.

Thanks for taking the time to read the manuscript and for sharing your thoughts.

Final reply:

We have chosen to remove the reference to Topotoolbox and TecDEM to remove the chance that a reader could misinterpret the status of these codes, which as Wolfgang notes, is not as black-and-white as their inclusion in this section suggested.

Response to A. Wickert

Dear Andy,

Thanks for taking the time to complete such a thorough review. As requested by the AE, please find below our replies to your comments. We've pasted each comment you made, then replied to it, and as necessary then copied in any modifications made in the text. We hope that these replies address your concerns to your satisfaction.

I also note that the process of pasting this text from Word to the ESurf online interface has resulted in our carefully formatted bullets now appearing as little inline "nu" symbols. Sorry! Hope this isn't too annoying.

Thanks again,

Dan (on behalf of all the authors)

Summary

Hobley and co-authors present Landlab, a toolkit that is poised to significantly change the face of Earth-surface modeling. I expect their framework to easily build and integrate models of the evolving Earth's surface to enable the community to improve – possibly rapidly – the state of our knowledge and theory of Earth-surface dynamics. On a personal note, I have followed the development of Landlab since its inception, and offer my enthusiastic support of the publication of this article that makes this comprehensive modeling infrastructure easy to follow in a way that mirrors the clean and well-written code base.

I recommend that the article be accepted for publication after some very minor technical corrections. As the article is, in my opinion, ready for publication, this review contains both technical notes and copyedits as a result of a very thorough read.

Main text

General: Many geomorphic models are run in 1 dimension. Is Landlab capable of solving 1-D problems? As I understand from my reading, it is designed for 2-D solutions, but it would be helpful to have a comment on this to clarify.

- Added to grid section: "Although Landlab grids are inherently two-dimensional, in many cases it is nonetheless possible to create an effectively one-dimensional simulation by creating a 3-by-N regular grid and closing the nodes along the top and bottom edges (see Section 3.1.4). Three-dimensional grids are not possible in Landlab at this time, though may be supported in a future release."

Page 4, line 9: I second Wolfgang Schwanghart's comment regarding open-source modules written in closed-source languages. Here, the algorithm may be known even if it cannot be run without the closed-source core programming language.

- We've simplified this section by removing reference to these 'open-source-but-on-a-closed-source-framework' type pieces of software, as the level of detail required to do the subject justice seemed a bit much for what is ultimately a tangent to the manuscript.

Page 6, line 9: Strong agreement regarding rapid prototyping. Based on reading the article, and having never used Landlab before (though having some familiarity with it), I was able to assemble a simple program for a class exercise in 1-2 hours.

- DH: Glad to hear we're achieving our targets in this area…!

Page 9, lines 6-10: Easy to note that this is standard right-hand-rule, if you think this is helpful.

- DH: Added: "…(i.e., the right-hand rule)…."

Page 10, "get" and "create" methods: I have seen "get" commands, such as "mg.get_grid_ydimension", that are exposed to the end user and have no underscore. So I must guess that there are two types of "get" commands, or... ?

- DH: Good catch. There are nine of these, and they are stragglers from before Landlab's internal style standardization. All have direct modernized equivalents, and they should be expunged in the final release of Landlab that goes alongside this paper.

Page 11, section 3.1.4: More a comment: the single set of boundaries implies to me that you have intended the model for discretization of only first and second derivatives.

- As you note, all current components operate only with first and second derivatives. However, it would be conceptually straightforward to create more boundary condition types as and when the need arises to accommodate higher order derivatives.

Page 12, line 16: Missing a noun between "ID" and "of".

- I don't think so; but nonetheless this comment indicates this phrasing isn't super clear. I've changed it a little to try to improve it: "By indexing these arrays with the IDs of element subsets, the values at specific locations and on each element type can be recovered."

Page 12, line 24: "Pairwise Transition Automata" appears, on Google and Google Scholar, only in this article, and its meaning is unknown to me. Could you elaborate?

- Modified to: 'For instance, pairwise transition automata (Narteau et al., 2001; 2009) represent the states of cells on a grid as paired "doublets", with rules prescribed to govern the rates of transition between each doublet type. These are readily implemented in Landlab by mapping the pair states onto the links of a Landlab grid, and representing the corresponding automaton cell states at grid nodes (Tucker et al., 2016).'

Page 13, line 20: What is “syntactic sugar”?

- We now explicitly define this (rather delightful) piece of computer science jargon: “Landlab offers some degree of “syntactic sugar” for its field name interface – i.e., the field interface is made more user-friendly by the addition of more readable grid properties to query the fields at each element type, rather than requiring the user to access the both dictionaries directly. For instance, `grid.at_node[‘my_field_name’]` is equivalent to `grid[‘node’][‘my_field_name’]`. In addition, Landlab also provides convenient shortcuts to create new fields of ones (`grid.add_ones`), zeros (`grid.add_zeros`), and from existing data (`grid.add_field`).”

Page 13, line 28: Missing hyphen for steady-state (modifies “solutions”)

- Added, and similarly at ln 29.

Page 15, line 18: Suggest replacing “However” with “While these are focused on Earth’s surface” (or “While these are Earth-surface focused”, if you like some dislike using the vestigial English genitive in scientific writing.

- We’ve settled on: “Although these existing components are largely Earth-surface focused, we emphasize that Landlab permits modeling of the evolution of almost any two-dimensional system that lends itself to description by discretized systems of differential equations or cellular automaton rules.”

Page 16, line 4: Having not thought about it before, it is not clear to me how you would combine a set of Jacobian matrices to, presumably, simultaneously solve an arbitrary number of coupled processes. It is probably just my ignorance, but I would like to see a bit of explanation and/or a reference.

- Given this remains entirely speculative material about future work, we’ve decided to remove this (admittedly pretty unclear) paragraph entirely, rather than invest the space needed to actually do this idea justice.

Page 16, line 9: changes → change; the word “data” is plural.

- Done

Page 17, line 19: Are “known correct solutions” all analytical solutions, or do you include solutions that go beyond this limited class of solutions? And/or, is “solutions” meant more generally – as in, is this also just making sure that general functions that you have programmed that may not be generating mathematical solutions are functioning as expected? As I type, I’m starting to think it must be the latter...

- Yep, the latter. I think this is strictly correct as written, and bringing up analytical solutions specifically implies that the unit tests are written only for the final solutions to differential equations in the components, which they are not. The grid is heavily tested too, for example. On this basis I don’t intend to make changes here.

Page 18, line 26: uplifting → uplift

- For maximum clarity: “…or other similar scenario with a radially symmetric uplift field.”

Page 20, line 15: More general question: Your method implies central differencing. How do you ensure that numerical diffusion is minimized and/or is not large enough to be important?

- This is indeed a central differencing method, as is widely deployed in handling diffusion problems in gridded models. However, our understanding is that numerical diffusion should only become an issue in advection-diffusion problems, or alternatively in upwinding schemes. This component as described here is neither, so a full discussion of the general issues around stability would seem a bit out of place at this point in the text (see also our reply to Campforts on numerical stability).

Page 21, line 8: Would this be the depth-integrated flux, as "flux" generally means [quantity/[area time]], so volumetric flux is L/t and therefore depth-integrated would become L2/t? Of course, Earth-system modelers use "flux" more liberally, but in a mathematics (and fluid mechanics), this is the use that I know, and I think it's best to be precise with language – especially considering how much you are in general.

- Indeed. We have added this wording.

Page 21, line 11: Again, more general question: if you are using the CFL condition, I am guessing that this is referring to something that is Euler forward. How would you choose time steps internally while using some of your implicit methods?

- I'm not sure which implicit methods you're referring to here. As emphasized in section 3.3.2, each component handles its own timestepping internally, and independently from all other components (see also Fig. 6). Thus in this specific case, the LinearDiffuser component is using a timestep governed by the CFL condition, while a putative separate implicit component would be using its own (longer?) internal timestep as governed by some other stability condition. The "coupling timestep" set by the user (sensu 3.3.2) is different again. I note that issues of timestep stability also came up in Campfort's comments, which resulted in some new text (now on p. 15) described in reply to him. Hopefully this text will also clarify things in relation to your comment here.

Page 22, Equation 9. Note ≥ is possible (≥) in LaTeX. There are also options to use curly brackets to make the conditional part of the equation clearer; see http://tex.stackexchange.com/questions/47170/ how-to-write-conditional-equations-with-one-sided-curly-brackets.

- This is not a LaTeX manuscript! This symbology was chosen largely as it mirrors that in Python. We'd absolutely be happy for the manuscript to be later typeset by ESurf like this…

Page 22, line 22. Near m/n, you may mention that this is the channel concavity. Perhaps, "m/n, i.e., channel concavity, ≈ 0.5.

- Added: "…interpreted from channel concavities of natural rivers at apparent topographic steady state."

Page 22, line 26. Remove "possible" (repeated later)

- Done

Page 23, line 2: Remove “performs as order-n, and as expected”: redundant. You could keep “as expected” if you like.

- We disagree that this is redundant; we wish to demonstrate that the component is performing as it should in terms of its scaling. We’ve left this.

Page 23, lines 3-4: “Broadly linearly” sounds strange: two dimension terms, the first metaphorical. How about “approximately”, or even just no modifier (it is so close to linear)?

- Modified to “close-to-linearly”

Page 23, lines 17-19: “based on...2001b).” is a repeat of text at the start of section 5.2 (p. 22, l. 2-6).

- We’ve deleted this text the first time it appears.

Page 23, line 20: “storm depth” to “stormwater depth” (or something like this)?

- “…storm water depth…”

Page 23, lines 24-25: “looped upon” to “called within the loop”, and remove “until...cease”. If I understand you here, this is a simpler way of writing this.

- Now “in other words, the code block below the generator will repeat with fresh values for each iteration until the total time is elapsed, at which point the loop will cease”

Page 23, line 28: “and where it only rains” to “with rainfall occurring” for better parallel structure

- Done

Page 25, line 5: remove comma after “region”

- Done

Page 25, line 6: remove “using” after “by”: unnecessary

- Done

Page 25, line 6: did you just write that stormwater depth is given by a gamma function? Also, “storm depth” should be turned into something like “stormwater depth” that makes more sense, per the above comment.

- Yeah, this was ambiguous as written. The durations are exponentially distributed, but the depths are gamma because they combine exponentials. The latter section is rephrased lightly to clarify. Changed also to “storm water depth”.

Page 25, line 9: Does Bras’ model incorporate latitude, integration over a day, etc.? And is it simple incident radiation (i.e. no diffuse or reflected)? I think that the latter is true from what you have written, but not sure about the former.

- This section has been expanded to address this explicitly: “The Radiation component calculates daily average extra-terrestrial and clear-sky shortwave radiation incident on a flat surface, based on latitude and day of the year (ASCE-EWRI, 2005). This component also calculates daily radiation ratio, defined as the ratio of cosine of solar angle of incidence for the true sloped surface to that for a flat surface (Bras, 1990).

The Radiation component does not explicitly calculate diffused and reflected radiation. The PotentialEvapotranspiration component uses the radiation ratio to calculate spatial net radiation using daily maximum and minimum temperature, and potential evapotranspiration (ASCE-EWRI, 2005; Zhou et al., 2013)." Note that we also had a reference manager issue with the reference that was formerly listed as "Snyder, 2005"; this should in fact have been rendered as "ASCE-EWRI, 2005" (a technical report chapter), as it now is.

Page 25, line 21: "and also" → "and"

- Done

Page 25, line 29: "shrubs cluster as they..."

- Much better! Done.

Page 26, line 12: "shallow" is ambiguous since you are writing about flow depth and slopes. I would write "low-slope" instead. Also, did you mean a different word than "urban"?

- Good call; did this. Also no, urban is right. The Bates algorithm was originally derived for use in city planning.

Page 26, line 29: "a uniform rainfall rate". Also, this is by filling the pits with water, I presume.

- I'm unclear what this comment is in reference to, sorry. The section around here seems OK to me, so I'm leaving it.

Page 28, line 4: You haven't mentioned visualization except for one reference to ParaView that you didn't follow up and a passing reference to matplotlib. Not actually a problem, but a note.

- This material was excluded mainly for reasons of manuscript length, and I think that's a decision we stand by. Lots more information about plotting and visualization can be found through the LL website.

Tables

Table 1b: What about raster D8?

- This gets at an aspect of Landlab's architecture which we have specifically not covered in this paper, because it is still fluid in the code: although it is possible to build rasters and rectilinear grids with diagonal node connections in version 1, the details of this are not exposed to the user at this stage, and may yet be modified. Essentially, Landlab doesn't view "diagonals" as true links (since they don't honour the graph theory rules that underlie Landlab's grid); any time they are invoked, they must be invoked separately from the true, orthogonal links. Since this functionality isn't user-facing, we've deliberately not covered it in this manuscript. I note that this was slightly ambiguous when we referred to "diagonal links" in table 2, so I've modified that description to now read "diagonal connections between nodes" (they aren't links!) This should make everything technically correct.

Table 2: Should rectilinear have rectangular cells, not "quasi-rectangular"?

- Not necessarily. This category also permits topologically warped rectangles (e.g., as in a global projection), should the user so desire.

Table 4: More of a comment: based on all boundaries being inactive, a 1D model in Landlab would have to have 3 × (N + 2) nodes. So it really isn't optimized for 1D, it seems.

- Certainly not optimized, no, but still perfectly capable. Landlab doesn't actually perform component calculations on inactive links in most cases, so it's only really an issue of overhead in grid setup. During the iteration of a run, it would run pretty efficiently in most cases.

Table 5: A nice set of modules... but at risk of sounding ungrateful of the large amount of work that this was, it would be really great to see a depositional components for Landlab appear... in case this isn't obvious, this is not a criticism of the paper, but more a comment on where this work could lead.

- Yep yep, this is very much on our minds (see also comments to Campfort's review).

Figures

Figure 3: Please ask copyeditors to ensure that this appears on the same page as Table 1.

- Noted.

Figure 4: Are patches numbered in order of min(max(surrounding nodes or links))? (Question inspired by (b)(ii).)

- Nope. Patches are ordered by centroid position (i.e., by corner), according to the same scheme as all the other element types as described in the main text. It's just a little unclear from this particular figure – which really focuses on the link directions – exactly where all the centroids are for these patches! I did in fact have to confirm this was right for myself, as it looks a little shonky.

Figure 7: Include line numbers. Also, flux → discharge, per our discussions? In addition, for this and the other figures with code, I am not sure if »> and ... are needed or are distracting... they are more the latter for me, I guess. But your decision in the end on style.

- In this case, we think "unit flux" is probably the right terminology, as it's a discharge per unit width of the face. We think we will retain the >>>'s here and elsewhere, as this style explicitly echoes the "doctesting" style in Python that users will see widely through Landlab's documentation. We think it would be good to introduce them to it here, rather than adopt a different style here and another in the online documentation.

Figure 8: You use both "base level" and "baselevel"; check for consistency (2x/each).

- We've committed to "base level". We also noticed that we had inconsistencies between "time step" and "timestep", which have now been unified as "timestep".

Figure 9: Why not combine this with Figure 8, if they make the same plot?

- We think having them separate is less confusing, as they appear separately in the text, and it would be hard to explain in the caption alone why both were being shown.

Figure 10: Please tell us how many cells you computed over to help readers gauge their own compute times.

- I'm unsure how this is different to what we are already showing here. LL generally regards nodes as the primary element type, so the figure gives speeds for numbers of nodes. Given these are simply nxn grids, users could easily compute numbers of nodes for themselves from the information given (e.g., ncells = (sqrt(nnodes)-2.)**2 for a raster). In most of these cases, it makes basically no difference whether we count nodes or cells.

Figure 14: (b) Vertical axis: PFT is more precise than plant type? Although this is clear from everything else. Legend: shown in parts (b) and (c) of this figure.

- We've chosen to leave this, as it seemed very minor.

Supplement

No concerns.

Testing

During the review process, I took advantage of the fact that I am teaching a geomorphology class to test Landlab. In our modeling lab, the students, most of whom have little experience in programming, were all able to install and run Landlab. In some cases, differences between computers and Python versions caused a little confusion, but the code itself worked well. The students are currently working using it with a simple coupled channel–hillslope model to (1) find relationships between hillslope diffusivity, the stream power coefficient, and the drainage area of the hillslope–channel transition, (2) investigate which factors lead to changes in the time it takes to reach steady-state conditions in a landscape, and (3) explore the effects of changing grids, uplift patterns, stream-power exponents, and more on the model results. The overall reception was very positive in this mixed undergraduate–graduate class, with students realizing through the model how real landscapes form and evolve. The code that I used, modified from one of those supplied in the paper, is attached below. I intend to teach the lab again.
One issue that I had while running this code on Linux within iPython is that the plotting tools would not release control of the shell to me (i.e. after plotting, I could not type anything more into the terminal, even after closing all of the graphical windows). This of course is not an issue to preclude publication, but I will add it as a ticket on GitHub.

- Thanks for this feedback, it's very valuable to us. Please do submit a ticket, though past experience of plotting issues suggests to us that this will be an issue arising from matplotlib's idiosyncrasies rather than an actual issue with Landlab. Nonetheless, we'll take a look.

Response to B. Campforts

Dear Benjamin,

Many thanks for completing this review for us. As requested by the AE, please find below our replies to your comments. We've pasted each comment you made, then replied to it, and as necessary then copied in any modifications made in the text. We hope that these replies address your concerns to your satisfaction.

I also note that the process of pasting this text from Word to the ESurf online interface has resulted in our carefully formatted bullets now appearing as little inline "nu" symbols. Sorry! Hope this isn't too annoying.

Thanks again,

Dan (on behalf of all the authors)

Review of Hobley et al. creative computing with Landlab

With Landlab, Hobley et al. present a refreshing framework to integrate numerical solutions for planetary surface processes. The model is fully open source and targets both end-users and developers providing an extended library of model structures and implementation strategies. The wealth in existing models and model structures makes the paper timely for the geophysical earth surface community and I recommend the paper for publication after consideration of some remarks.

Before reading the paper and because of its intention: i.e. providing an integrative numerical modeling toolkit, I formulated some questions which I would like to see addressed in such a paper. In the following I list those questions and discuss to what extend I found satisfying answers and where the paper can be improved.

* General ease of use of the numerical model.
I congratulate the authors for their well-functioning and carefully documented source codes.

- Thanks!

* Debugging tools
I highly value the availability of unit tests to evaluate the model code. This is one of the aspects in which Landlab differentiates from other numerical earth surface models.

- Again, thanks. Good to be reassured that effort on this front has been worth it…!

* Input/output data structures. Compatibility with other tools available.
Well implemented and properly discussed in the paper

- Thanks.

* Discretization of the continuous solution to grids. Shifting between different kind of grids.

Another major contribution of the paper is the way in which different discretization schemes and the numerical grids which come with them are presented. Nonetheless, while reading section 3.1, I sometimes had the feeling reading technical notes rather than a paper on earth surface dynamics. I propose that the authors discuss, somewhere in this section, the importance of different grid implementations and its relevance for the field of earth surface dynamics. E.g. the use of structured grids has major implications in terms of landscape symmetry as elegantly documented by Braun and Sambridge (1997). It would also be interesting to briefly discuss the implications of using raster versus voronoi grids and to what extent the model supports conversion between the methods. A first example which comes to mind in the framework of LEMs (which is only partly what the model is designed for) is the simulation of tectonic shortening which is often executed on irregular grids (Willett, 1999), whereas other landscape processes such as nonlinear diffusion (Perron, 2011) might benefit from structured grids for computational performance. Does the grid structure of the model allows for grid refinement (e.g. Künze and Lunati, 2012)?

- The first of these points is a good idea, but we feel we've already done this fairly well in the manuscript. The paragraph now at p. 8 lns 17-24 covers this ground at a level we already thought was commensurate with the scale of this paper, and indeed does already briefly touch on Braun & Sambridge's insights. Nonetheless, we have added an additional clause with a little more detail from Braun & Sambridge ("Irregular grids avoid some of the cardinal direction artifacts than can form on regular grids, such as linear networks and linear drainage divides, **as well as consequent biases in measured channel metrics like drainage density, river length, and channel slope** (Braun & Sambridge, 1997).") Regarding the later comments here, however, we are reluctant to expand too much on what we have regarding explicit conversion between grid types. Landlab is not, and is not really at this time ever intended to be, a GIS tool. Operations like interpolation between grids are better accomplished in other, more specialised software in our view. At the moment, in part for similar reasons and also simply because of the lack of a pressing application, we do not allow grid refinement or densification. Past experience of some of the Landlab team (GT, NG) with CHILD – which does support this kind of ad-hoc grid modification in some instances – suggests that this kind of process can be extremely challenging to implement. This would only be more so in Landlab, where densification would need to be accommodated not only within the grid, but its consequences also propagated out into many of the components. Nonetheless, we do intend that future versions of Landab may explicitly support grid deformation, if not refinement per se. That all said, we should probably also note that specifically regarding comparison between results obtained from different grid types, this is an active field of research for the Landlab team (see, e.g., Gasparini et al., Eos Trans AGU 2014, EP51E-3564), and future publications will address this issue specifically.

* Parallelization and suitability for supercomputing
One essential asset of a robust model structure, especially if the authors target a large user community, is the possibility to port the source code to a larger computer infrastructure. This item is currently not covered in the paper and it would be good to discuss on the potential of Landlab to be parallelized and the limitations which comes with it. In case the model supports parallelization, how do you take care for changing drainage areas while executing the model on different computational blocks?

- Again, this material was not present in the paper primarily for reasons of space in what is already a long manuscript. As you are of course alluding to, parallelizing a heavily componentized software architecture is significantly more challenging than a fully compiled and stable code, as the programmer can not necessarily know ahead of time the sequencing of the calls to various parts of the code. This more or less rules out the idea of "parallelizing Landlab" in the broadest sense. However, parallelization is much more possible within individual components – and is implemented in Flexure, as proof of concept. However, given your explicit interest, we've added a short additional section:

"3.3.3 Parallelization

Together, the componentized nature of Landlab and the level of flexibility afforded to the user conspire to rule out the idea of Landlab as a whole being highly optimized through parallelization. However, there is great potential for parallelization of Landlab at the component level, since the run methods of each component are entirely self-contained. As proof of concept, the Flexure component has already been parallelized (see online code and documentation). Although in Landlab version 1.0 we have not had a compelling enough use case to invest significant time in such work, many of the components already in the library would be amenable to parallelization in this style, and this could be done in future releases."

* 3 spatial dimensions
Many earth surface processes require a 3-dimensional spatial discretization. Amongst others: hydrological processes, ice dynamics, terrestrial heat advection and diffusion, and soil dynamics. As the authors explicitly state that Landlab "is not a landscape evolution model ...rather, it presents a framework under which a wide variety of models can be implemented using it tools, including hydrologic ...", I am a little surprised that the use of a third spatial dimension is never mentioned in the text. I do not suggest that the 3rd dimension should be included in the current release of the software but I would find it interesting to see a discussion on the possibility of adding a third spatial dimension to the model.

- I'm assuming here that you are simply advocating that we discuss whether Landlab be able to run three dimensional grids. I don't feel this is necessarily close enough to the remit of Landlab (which is at the moment, fundamentally, a two-dimensional framework), as we set it out in the introduction, to be worth spending time on in the manuscript.

* Numerical accuracy.
During last decades, many numerical models have been developed mainly focusing on (i) earth surface processes being simulated or (ii) the performance of the numerical simulations. Much less attention has been given to the numerical accuracy of the developed models. This issue is also not very well covered in this manuscript. Nonetheless, recent work has shown that numerical accuracy significantly influences model performance, not only when topographical knickpoints are present but also when lateral displacement of topography needs to be accounted for (Campforts et al., 2016; Campforts and Govers, 2015). Moreover, it would be good that Landlab also offers some analytical solutions for the

numerical processes being simulated or that the authors discuss how this could be achieved as analytical solutions are the benchmark against which different solution strategies can be evaluated. As such, a benchmark solution would be available which cannot only serve as a tool to evaluate the accuracy of the current model structure but is also of aid to new users in order to test new models and numerical solutions. For example, an analytical solution for the stream power model can be quite easily found using the slope patch solution of Royden and Perron (2013) but also for numerical solutions not directly related to landscape evolution, analytical solutions do exist (Stüwe et al., 1994). Numerical accuracy is sometimes mentioned throughout the text (e.g. when discussing the influence of timesteps on line 30, p. 15) but it would be good to elaborate on this point and cover this relevant issue in more detail

- As you note, this manuscript does not dwell on issues of computational accuracy. However, this is mainly because this text is focused on the functionality of Landlab as a whole, whereas issues of numerical accuracy are relevant to each component individually. On this basis, we would prefer not to greatly expand our coverage of this issue; rather, it will be discussed as relevant in future publications which are focused on each novel component in turn. For instance, Adams et al., in review, doi: 10.5194/gmd-2016-277 does this in some detail for the implementation of the overland flow model in section 5.4; a manuscript in prep from Siddhartha Nudurupati on the vegetation CA seen in section 5.3 does something similar for that component. [I should also note as an aside that the Adams et al. manuscript is now citeable in review at GMD, so we have reinstated references to it in the text as appropriate.] Likewise, the diffusional and stream power models illustrated in sections 5.1 and 5.2 are simply reimplementations of algorithms already comprehensively described by other authors; existing publications describing those schemes specifically (c.f. Braun & Willett, 2013 for stream power; e.g. Slingerland & Kump, 2011, Chapter 5 for discussion of central differencing schemes for diffusion) already provide much of this information, and we assert that it is not necessary to repeat here.

* To what extend is the model oriented towards integration of measured data into the numerical model?
Major advances can be made in the field of earth surface processes by combining numerical models with field data (Fox et al., 2015; Glotzbach, 2015). I think the framework presented in this paper offers an excellent opportunity for such an approach and could be of high value for otherwise more data oriented researchers. It would be interesting to see some explicit suggestions or remarks on how to combine the Landlab framework with field data.

- In the interests of space and keeping the manuscript focused, we chose not to include this material. We should also re-emphasise that this kind of functionality will probably appear at the component level, so would be best addressed in future, component-level publications. We anticipate that there will be a good number of these, and indeed, forthcoming publications from the core team (e.g., Siddhartha Nudurupati et al., in prep; Hobley et al., in prep) are already making strides in this direction.

* Particle tracking

One very interesting aspect of numerical models is to trace back particles through time. I am wondering whether Landlab allows fingerprinting of for example sediments. Is it possible to track a sediment particle all the way from the hillslopes to the outlet of the drainage network? Can this be done for all particles and how feasible is that in terms of memory allocation and data storage? Particle tracking would offer great potential for the model to be further combined with e.g. detrital dating methods (thermochron data (Herman et al., 2015)/ CRN data (Mudd, 2016))).

- This is indeed an interesting aspect, and we very much intend for future components to include a particle tracker. However, given that (as Wickert also noted) the current suite of components at version 1.0 is not particularly sediment- or deposition-orientated, we haven't prioritized this functionality, and it seems unnecessary to speculate on it here without having the work in hand.

* An interoperability interface

In the abstract, Landlab is presented as a modular framework with a strong interoperability. The paper comes up to this promise and presents four contrasting model designs. I enjoyed reading these sections and I think they strongly contribute to the illustrative nature of the paper. Nonetheless, I think this section could be even stronger if the authors also point out the advantage having the different model approaches under the roof of one single model infrastructure. In my opinion, one of the main assets of Landlab is not necessarily the capacity to execute separate model designs but exactly that they can be combined. For example, until now, little attention has been given to the role of vegetation in landscape evolution models. Nonetheless, it has been shown that vegetation might have a very strong influence on landscape evolution (Collins, 2004). The cellular automaton presented in sections 5.3 could therefore be neatly integrated with section 5.1 and/or 5.2. Likewise, hydrological processes are shown to govern stochastic processes like shallow landsliding (Montgomery and Dietrich, 1994). Hence section 5.4 can be perfectly linked up with the other sections. I would keep the sections in their current form as they are very illustrative of the model performance but it would be definitely nice to discuss and eventually illustrate the potential to integrate all or some of these modules.

- We had hoped that this point was coming across strongly enough already, but we're happy to address this a bit more forcefully. We've added "We hope that these examples will also serve as an illustration of the potential power of the Landlab framework to enable novel or under-explored process interaction studies (e.g., of vegetation on landscape evolution; of surface hydrology on stochastic surface processes)"… to the introduction of section 5.

Minor comments

Overall the paper is very fluently written and I enjoyed reading it. I endorse the comments of W. Schwanghart and A Wickert. In addition, I have a few minor comments:
Page 2-5: Introduction. I get the point the authors try to make but the way the introduction is written feels like the authors want to promote their product as the one and single framework to be used for future model development. Although I agree with the authors that the structure they provide can offer excellent guidance for new model development and the 'gridding engine' can definitely save many hours of numerical coding headache, I

am not so sure whether I agree it is a good idea to demotivate building code from scratch. The latter is still the best way to become familiar with the implications and limitations which come with numerical software design and to realize to power and caveats of numerical models. I second W. Schwanghart's comment in suggesting that many open source initiatives exist, although sometimes written in commercial software (e.g. TopoToolbox and the LEM TTLEM is fully open access; SIGNUM (Refice et al., 2012)) or even in Python, advanced GIS packages are available (LSDTopoTools https://github.com/LSDtopotools).

- We aren't sure what exactly we can change here (outwith our modifications pertinent to Wolfgang's comment). It is certainly not our intention to demotivate future readers to code up stuff for themselves! That said, it's clearly the purpose of this manuscript to set out Landlab's shop stall. We've made a couple of minor tweaks to the language used to emphasise more that the issues described here pertain specifically to issues for professional research scientists who just want to produce high quality software, and don't necessarily carry over to considerations around learning or skill acquisition (See track changes in paragraph 2, p. 2). Hopefully a future publication in a different forum will expound on Landlab's advantages as a pedagogical environment.

Page 10, line 24: Analytical method. I would use a different wording as analytical typically refers to the analytical solution of e.g. PDE's. What about grid methods?

- Good call on changing this. We've selected "Computational methods".

Page 15-16, line 23-5: I find this very interesting. Does the model allow for constraints on the timestep in the case that implicit methods are being used? Although they are indeed unconditionally stable, the use of large (main model) timesteps in LEMs might result in in very sudden topographical changes causing the presence of artificial steps in the landscape. E.g using an uplift rate of 1mm/yr in combination with timesteps of 10ky results in a sudden uplift of 10m in the LEM which initiates artificial knickpoints at the baselevel of rivers.

- Aha, good question. As is implied (though I don't think outright stated) in this section and its associated figure, when Landlab has a truly or at least largely implicit solution, it does _not_ seek to impose any internal restrictions on that timestep. As you rightly note, this runs the risk that the user can take inappropriately long timesteps. We agonised about this, but decided that in a very flexible environment like Landlab, adding arbitrary timestep restrictions on implicit methods would create more problems and confusion than it would solve. In such cases, the component documentation normally makes reference to this issue, and the user is encouraged to think about it for themselves – the "appropriate timestep" would be very much situation dependent, so we can't really legislate for it in a general way. We've added a sentence here to make explicit for the reader that this is indeed "a thing": "Note also that where components employ implicit solutions, there may be no internal limit to the timestep at all (e.g., Braun and Willett's (2013) Fastscape algorithms for stream power). In such cases, Landlab will make no check on the imposed timestep, and the user must ensure that the imposed *dt* is appropriate under the boundary and initial conditions that they are running. For instance, the Braun-Willett algorithm ceases to behave in a truly timestep-independent fashion under transient conditions, but in a way that still permits timesteps larger than would be imposed under an explicit Courant condition (for more details see their Appendix B).

> However, those authors did not propose an alternative scheme to limit the timestep in such cases, and consequently Landlab also does not. A user of this component is assumed to have read the component documentation and taken on board that this is potentially an issue, and to have taken steps to check that their output is behaving sensibly and is not highly sensitive to changes in the supplied timestep. We reiterate that it is ultimately the user's responsibility to check that the provided *dt* is appropriate to the modelling scenario in hand."

Page 18-19: nice illustration on the use of finite volume methods.

Page 22, line 31: what about maximum timesteps for implicit schemes? See comment above (Page 15-16)

- Now addressed explicitly in that section.

Page 24 line 22: I would get rid of the sentence starting with Figure 13. I also do not see the additional value of Fig 13 for this paper.

- We would prefer to retain the figure, as it neatly encapsulates a key functionality of Landlab that isn't well illustrated in any of the other figures.

Figures

Great figures in general.

Figure 1: Nice images but I find it a missed opportunity to illustrate the broad range of problems Landlab itself is capable to simulate.

- In principle, Landlab would be able to simulate any and all of these processes, given a motivated user. In most of these cases, moves are already afoot to add these functions into Landlab for a future release…

Not sure what the additional value of the code snippets is. Personally, I find the Landlab wiki page much more insightful in this perspective.

- While we definitely would want a user to look at the wiki, we wanted this paper to be able to stand alone, without forcing a reader to go online to get more resources. Hence we have included the code snippets in the text.

Testing:

I am not very familiar with python and I second the comments of referee 1 who did elaborate testing with a large user group. Nevertheless, I installed the software and executed some of the tutorials which I found very easy to understand and clearly documented. I had no single problem when executing the code. A very small suggestion would be to add a link to the 'coupled_params_storms.txt' file in the 'Getting to know the Landlab component library' tutorial on https://nbviewer.jupyter.org/github/landlab/tutorials/blob/master/component_tutorial/component_tutorial.ipynb, similar to the link given for the 'coupled_params.txt' file.

- Thanks for the recommendation. I'll add it as a ticket on Github.

Creative computing with Landlab: an open-source toolkit for building, coupling, and exploring two-dimensional numerical models of Earth-surface dynamics

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Abstract. The ability to model surface processes and to couple them to both subsurface and atmospheric regimes has proven invaluable to research in the Earth and planetary sciences. However, creating a new model typically demands a very large investment of time, and modifying an existing model to address a new problem typically means the new work is constrained to its detriment by model adaptations for a different problem. Landlab is an open-source software framework explicitly designed to accelerate the development of new process models by providing: 1. a set of tools and existing grid structures – including both regular and irregular grids – to make it faster and easier to develop new process components, or numerical implementations of physical processes; 2. a suite of stable, modular, and interoperable process components that can be combined to create an integrated model; and 3. a set of tools for data input, output, manipulation, and visualization. A set of example models built with these components is also provided. Landlab's structure makes it ideal not only for fully developed modelling applications, but also for model prototyping and classroom use. Because of its modular nature, it can also act as a platform for model intercomparison and epistemic uncertainty and sensitivity analyses. Landlab exposes a standardized model interoperability interface, and is able to couple to third party models and software. Landlab also offers tools to allow the creation of cellular automata, and allows native coupling of such models to more traditional continuous differential equation-based modules. We illustrate the principles of component coupling in Landlab using a model of landform evolution, a cellular ecohydrologic model, and a flood-wave routing model.

1 Introduction and motivation

Across a wide array of fields, researchers use numerical models to study processes that operate on and across the Earth's land surface and shallow subsurface. Science and engineering applications of these models of surface dynamics range from short-term flood forecasting (e.g., Horritt and Bates, 2002) to simulating the evolution of Earth's landscape over geologic epochs (e.g., Tucker and Hancock, 2010). Models may focus on a theoretical understanding of processes and their interaction, on management or engineering applications, or on predicting environmental responses to natural or human-made perturbations. Although the processes and temporal and spatial scales vary widely, the software behind these models is often quite similar. For example, most Earth surface dynamics models manage data structures and algorithms to represent a terrain surface and its connectivity, and many include solution algorithms to compute flows of mass (such as ice, liquid water, sediment, or chemical nutrients) across terrain (Slingerland and Kump, 2011) (Fig. 1).

However, scientists who want to use an Earth surface model often build their own unique model from the ground up, re-coding the basic building blocks of their model rather than taking advantage of codes that have already been written (Adams et al., 2014; Katz et al., 2015; Overeem et al., 2013). This undoubtedly does produce novel software capable of fulfilling its designer's needs, and can have advantages in helping the programmer to acquire a total understanding of the code base, but this approach also has many associated problems; many person-hours are lost rewriting existing code, and the resulting software is often idiosyncratic, *ad hoc*, undocumented, and unable to interact with other software programs both in the same scientific community and beyond. In particular, models are often initially written to solve a very specific problem, rather than to provide a flexible and reliable platform for solving a general class of problems (Easterbrook, 2014). It may also become impossible for a single programmer to maintain their grasp of their code base once it exceeds a certain size. A result is that software development often acts as a bottleneck to progress, with frequent duplication of effort as research groups struggle to adapt existing software or develop new code from the ground up as each new research problem emerges.

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The Landlab modelling framework described here seeks to mitigate these redundancies and lost opportunities and simultaneously lower the bar for entry into numerical modelling. The approach is to create a user- and developer-friendly modelling environment that provides scientists with the fundamental building blocks needed for modelling surface dynamics on the Earth, and potentially beyond. The framework takes advantage of the fact that nearly all surface-dynamics models share a set of common software elements, despite the wide range of processes and scales that they encompass (Peckham et al., 2013; Slingerland and Kump, 2011). Providing these elements in the context of the popular scientific programming language Python, and with strong user support and community engagement, would contribute to accelerating progress in the diverse sciences of the Earth's surface.

From the user's perspective, Landlab enables the following:

1. Rapid, easy creation of a number of distinct geometric *grids*, with all the connectivity between various elements already defined, and the ability to create two-dimensional data fields across a given grid;
2. Functions to operate on the values defined on such a grid, enabling the solution of time-dependent numerical algorithms across them (e.g., differential equations, cellular automata);
3. A mechanism for the control of boundary conditions across a grid;
4. Encapsulation of conceptual models for individual Earth-surface processes into reusable *components*, with a standard interface that allows operation across Landlab grids;
5. The ability to build a multi-process model by combining together components;
6. The ability to quickly and efficiently build new components, and to couple them with those components already in the library.
7. A straightforward and standardized input and output interface, including the ability to import from and export to common spatially distributed data formats such as NetCDF and ESRI ASCII, and a plotting module. This interface also enables coupling to third party models and software.

2 Approach

2.1 Guiding design principles

The design principles for Landlab have been guided both by our observations of current software design practices in the surface-system modelling community, and by white papers issued by existing organisations both within this community (Adams et al., 2014; Overeem et al., 2013; Peckham et al., 2013) and in the scientific software design community more widely (Becker et al., 2015; Chue Hong, 2014; Katz et al., 2015; NSF, 2012). Our key observations are that:

1. Many models exist that simulate Earth surface processes, and many of these share a very similar underpinning in terms of the basics of grid construction and the suite of simulated processes. This set of models represents significant past duplicative effort in the surface process modelling community. Although the reasons for duplication are likely multiple and vary from group to group, we note that we are unaware of previous efforts to advertise a flexible, open-source programming framework.
2. Orphaned or unmaintained codes are common in the research community, having been built for a single purpose and then set aside.
3. Although standardized frameworks for model interoperability are now in place (such as the framework designed and maintained by the Community Surface Dynamics Modelling System (CSDMS) group (Hutton et al., 2014; Overeem et al., 2013; Peckham et al., 2013)), many models are not compatible with these standards. We

hypothesize this is largely due to the effort required by the original programmer to modify legacy code – which in many cases was written before the standards were established – to meet these new interoperability criteria.

4. Existing model software tends to have a high bar to entry. Many models are written in compiled languages, such as Fortran, C, and C++ (examples from the geomorphology and sedimentary stratigraphy communities include CHILD (Tucker et al., 2001b), Sedflux (Hutton and Syvitski, 2008), MARSSIM (Howard, 2007), Fastscape (Braun and Willett, 2013), DAC (Goren et al., 2014), SIBERIA (Willgoose et al., 1991a; 1991b)). This requires the prospective user be fluent in these languages before the code can be modified, or in many cases, even used efficiently. Because many legacy codes were not designed to be shared amongst the community, documentation, both in-line and external, tends to be idiosyncratic at best and missing at worst.
5. In several instances, scientific software with a broad user base exists, but remains closed source. This includes both tools for data analysis (e.g., ArcMap, Matlab) and in some cases the modelling software itself (e.g., FLAC (Itasca, 2000), Dionisos (Granjeon and Joseph, 1999)). Where software has to be purchased, this presents obvious barriers to wide uptake of modelling approaches using these tools in terms of financial cost for the user. More importantly, all closed source software also presents significant barriers to code assessment in peer review and to reproducibility of the work (Crick et al., 2014; Katz et al., 2015).

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These observations lead us to a set of key design principles that have governed our development of Landlab:

A. Landlab should be a community resource, and thus fully **open source**.
B. Landlab should provide a development environment that is **flexible, extensible, and highly reusable**.
C. Landlab should be written in a language that allows **rapid development** of new code.
D. Landlab should be fully compliant with the CSDMS model interoperability standards (Peckham et al., 2013) from the ground up, and this compliance should be built into the low-level development framework itself. Thus, for example, components written in Landlab will be automatically compliant with these standards.
E. Landlab should have a **low bar to entry**, and be thoroughly **documented**. Tutorials should be present. It should be possible for a beginner to use Landlab without a full grasp of the underlying model architecture, in a "plug and play" fashion.
F. Landlab's code needs to be **sustainable**, as detailed below.

2.2 Low level design choices

In turn, these guiding design principles directed early decisions in terms of Landlab's coding language, architecture, and distribution.

Open source availability. Landlab is licensed under the MIT free software license, an approved license of the Open Source Initiative. This license allows a user to deal in the software without restriction, including without limitation the rights to use, copy, modify, merge, publish, distribute, sublicense, and/or sell copies of the software. The source code and associated files are maintained in a git version-control repository, for which the master repository is presently hosted on the GitHub website, https://github.com/landlab/landlab. Release versions are also freely available through the *pip* and *conda* Python package managers. The model repository maintained by CSDMS offers links to Landlab documentation and to the GitHub repository, increasing Landlab's visibility to the surface process modelling community in particular. Web-based documentation is hosted at http://landlab.github.io. This includes both developer-written summary documents and tutorials, as well as reference-level documentation that is automatically generated from inline comments and examples in the code itself.

Programming language. Landlab is written in Python and exploits and includes as dependencies a number of widely used scientific Python packages: numpy, scipy, matplotlib, nose, netCDF4, numpydoc, cython, six, pyyaml, setuptools, and libgcc. The decision to write in Python was explicitly made to lower the bar for entry to Landlab, to increase the flexibility and reusability of the code base, and to increase development speed both for the core development team and for future users. Informal canvassing amongst the surface process community, especially amongst graduate students and other early-career scientists less likely to already be strongly wedded to a certain development environment, revealed a marked preference for – and greater familiarity with – Python over C++ (other open-source languages were rarely mentioned). This changing preference for Python has also been noted for PhD students in general, beyond just the field of surface process modelling (Chue Hong, 2014). The choice of Python also means that developers using Landlab can take advantage of that language's affinity for rapid development (Prechelt, 2000). In particular, Python's dynamic typing and interpreted rather than compiled implementation remove the developer's need to deal explicitly with memory management (van Rossum and Drake, 2001). Other advantages of this choice include high portability between platforms, open-source language, numerous existing scientific libraries, and support for selective optimization of time-critical parts of the code base using Cython and/or compiled-language extensions. Cython is a compiled language that is a super-set of Python, and Cython extension modules interact seamlessly with pure Python. However, program modules written in Cython allow more granular control of memory management than is the case in pure Python, which can result in significant acceleration of code. Cython is already in use within Landlab for sections of the code that require long out-of-sequence iterations through arrays, and other sections where pure Python would tend to have poor performance. For example, Cython is used in the construction of some of the grid element connectivity arrays, in the FlowRouter and FastscapeEroder components, and in the CellLab extension to Landlab (Tucker et al., 2016).

Code sustainability. A key objective for Landlab from inception has been that the code base be sustainable (Adams et al., 2014; Becker et al., 2015; Katz et al., 2015; Stewart et al., 2010). Following other authors, we view sustainable software as that which is able to continue effectively, sustaining or improving its functionality through time while at the same time adding new users. Stewart et al. (2010) drew attention to a number of key features of sustainable software, which we have sought to implement. These are:

- *Strong, consistent leadership.* The authors of this paper represent the core development team of Landlab.
- *Rapid prototyping and evolutionary design*. Landlab was initially developed to fill the immediate research needs of the core development team, giving it a strong and well-defined initial direction. In this initial development phase, we have emphasized long-term mountain belt evolution modelling; steady- and nonsteady-flow routing; eco-, surface, and shallow subsurface hydrology; hillslope dynamics; cellular automaton modelling; vegetation dynamics; and ecosystem dynamics. However, the explicitly modular nature of Landlab means that it can readily adapt to new scientific objectives and expand to meet new and as yet unforeseen demands in the future.
- *Modern and effective software engineering practices*. Landlab takes advantage of a number of best practice processes, including extensive and automated unit testing of key code functionality, a formal bug- and issue-tracking record implemented through GitHub, cross-team review of code changes before they are merged into the master branch, and thorough code documentation. A significant portion of our online documentation is created semi-automatically from inline code comments. This reduces duplication of information and aids maintenance and updating of the documentation as the code changes. Individual functions and classes are documented automatically using Python's docstring functionality. General descriptive documentation and tutorials are created and maintained manually. Auto-generated documentation is updated and posted to the project website automatically as new code changes are committed to the GitHub repository using "webhook" functionality provided through the http://readthedocs.org website.
- *Sustained compatibility with underlying libraries, protocols and operating systems*. Landlab is compatible both with Python 2 and 3. The code base is tested automatically using Travis (Mac, Unix) and Appveyor (PC) continuous integration platforms, across Python versions 2.7, 3.4, and 3.5 (see also Section 4).
- *Dissemination and community understanding*. We have sought to publicize Landlab widely at a number of international conferences and workshops, classes, and through collaborative networks. We estimate that at as of mid-2016 approximately 330 potential users have now seen or participated in Landlab-based presentations or classes.
- *Encouraging collaborative software development*. Landlab enables users to tailor its functionality to their specific needs, through its modular design and flexible grid and grid functions. We are already aware of a number of groups outside the core Landlab development team working with Landlab for their own research purposes.

A secondary aspect to sustainability is the ability to have the software continue to be useable after the active development cycle has ceased (Stewart et al., 2010). We anticipate that the choice of Python, minimal system and extension package requirements, open-source availability of our code base, and thorough documentation will sustain our code for the foreseeable future.

3 Model Architecture

Landlab has an essentially tripartite structure – a core grid module, a library of process components, and a set of supporting utilities (Fig. 2). The various subdivisions of the code behave as Python modules, and can be imported and used within a Python environment independently.

3.1 Landlab's Gridding Engine

Landlab provides the ability to create a two-dimensional simulation grid of a user-specified size and shape, with a single line of code. Grids are represented as Python objects; a grid object includes data describing its geometry and topology, as well as a variety of methods and functions to manage data and perform common numerical operations. (In object-oriented programming parlance, a *method* is a procedure associated with an object; in this case, "method" means a function that is defined within the grid class, and that can be accessed with the "`grid.method()`" syntax typical of other class properties.)

Although Landlab grids are inherently two-dimensional, in many cases it is nonetheless possible to create an effectively one-dimensional simulation by creating a 3-by-N regular grid and closing the nodes along the top and bottom edges (see Section 3.1.4). Three-dimensional grids are not possible in Landlab at this time, though may be supported in a future release.

3.1.1 Grid types and elements

A Landlab grid is defined by a set of grid primitive elements: nodes, links, cells, corners, faces, and patches (fig. 3). In terms of graph theory, these can be thought of as two interlocking and offset sets of points (nodes vs. corners), edges (links vs. faces), and areas (patches vs. cells). The entire grid can be generated from a description of the geometry of only one of these element types – typically, a user might specify the locations of the nodes, and the grid object's remaining elements are automatically placed according to this node framework.

Each element type shares unique one-to-one or one-to-many geometric mappings with the other elements. Were the grids to be infinite, these mappings would be perfectly reciprocal – the topology and connectivity of each element with respect to every other element would be identical everywhere it occurs. However, because these grids are finite, we must arbitrarily decide whether the bounding elements are nodes-links-patches or corners-faces-cells. We have chosen the former (see Figs. 4, 5), which means that for example, while all cells have nodes, not all nodes have cells – as the nodes at the grid perimeter cannot have cells defined around them. Table 1a lists the unique one-to-one mappings of features, and emphasizes which element defines the grid edge in each case. Table 1b lists the primary one-to-many relationships defined for each element type, and lists the standard number of mapped elements (if well defined) for each of the primary grid classes. Note that this table only lists the most useful identities within the three-element groupings node-link-patch and cell-face-corner. The other identities also exist, and can be reconstructed from the one-to-one identities in Table 1a.

Data can be assigned to any element of the grid (see Section 3.2, below). The grid classes also provide properties that define and describe the geometric interrelationships amongst these grid elements (see, e.g., Fig. 4). These mappings allow common geometric operations (such as calculation of gradients across the grid, finding maximum/minimum/mean values of neighbors, upwinding schemes, and flux divergences) to be achieved in typically one or two lines of code.

Landlab provides native support for both regular and irregular grids (Figs. 3, 4). Treating both grid types natively within Landlab allows the grid to be tailored to specific applications. For example, raster grids provide compatibility with digital elevation model data, and can in some cases allow better optimized process algorithms. Trigonal grids with hexagonal cells provide an additional axis of symmetry, and obviate the need for handling diagonal connections in certain types of numerical algorithm (such as flow routing, e.g., Jenson and Domingue, 1988). Irregular grids avoid some of the cardinal direction artifacts than can form on regular grids, such as linear networks and linear drainage divides, as well as consequent biases in measured channel metrics like drainage density, river length, and channel slope (Braun and Sambridge, 1997).

Regular grids with quadrilateral cells are implemented as rasters, and irregular grids and all other regular configurations (e.g., hexagons) are implemented as Voronoi-Delaunay interlocked meshes, as also used in the landscape evolution models CASCADE (Braun and Sambridge, 1997) and CHILD (Tucker et al., 2001b). Grid subtypes are defined within these broad families (Table 2). Landlab also implements a base grid class (“ModelGrid”) from which both the raster and Voronoi-Delaunay grids are derived. This class describes the elements of the grid and allows their geometries and topologies to be set, but defines no rules for how to do this. This base grid class is primarily intended as a framework from which to derive new grid architectures, rather than as a usable grid type in isolation.

Although the grid primitive element set is shared between the various grid types, the implementation of the geometries is slightly different. For example, core nodes in a raster grid will always have exactly four links, whereas they may have any number of links in a Voronoi-centered irregular grid (Table 1b, Fig. 3). Similarly, methods defined for the grid may be polymorphic or overloaded to optimize functionality for each grid type.

3.1.2 Grid standardization and conventions

All Landlab grids share an identical scheme for the numbering of their elements. All elements are numbered from the bottom left of the grid, starting with an ID of 0. All features are ordered first by y coordinate, then by x, taking the midpoint (for linear features such as faces or links) or geometric center (for areas such as cells or patches) for non-point elements as necessary (Fig. 4).

For rotational ordering, Landlab adopts the mathematical standard convention of *counterclockwise from the positive x axis* (i.e., the right-hand rule). This applies not only to almost all measured angles (unless otherwise explicitly noted), but also to the ordering of elements around other elements (such as links around a node), and to the ordering of grid edges where needed (i.e., the standard order is right-top-left-bottom edges). Simple ordering examples are illustrated in Fig. 4.

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We extend this same rotational convention to define the directionality of all linear elements (such as links and, where necessary, faces), when such directionality is required. The positive direction is associated with the top-right (first) quadrant; in other words, the positive direction is the one that points more right than down or more up than left. This is shown in more detail in Fig. 4b. This kind of directionality is important for example in the definition of fluxes along links into and out of nodes. In the case of link directions, Landlab provides masking arrays that can describe the local orientation of each link with respect to another feature; for instance, `link_dirs_at_node` describes whether a link points into (+1) or out of (-1) any given node. The use and utility of such data structures is illustrated in Section 5.

3.1.3 Mappings and grid characteristics

Landlab uses a standardized grammar to describe the methods and Python properties in the grid classes that provide information about the mapping of grid elements onto other elements, and to obtain information about the grid (e.g., areas, lengths, gradients). The intention of this standardization is to both make it easier for users to quickly find the method they require, and also to provide information on the computational efficiency of the operation. Some of this information is summarized in Table 3.

Grid characteristics. Landlab grids provide Python properties to describe the geometric characteristics of the elements themselves, for instance, position, dimension. These properties are denoted by the preposition “of”, as in, for example, `width_of_face`, `length_of_link`, and `area_of_cell`. Use of the word *of* tells the user that an array of floats (or, more rarely, integers) denoting a grid characteristic is the expected return. (See for example use of `angle_of_link` in Fig. 4b.) *Of* is also used to access many counted characteristics of the grid as a whole, such as `number_of_nodes`. All these properties return pre-allocated arrays or single values already stored in memory, and can be expected to be fast.

Grid element mappings. The grid also provides numerous Python properties that describe the connectivity and associations of elements with one another. These are denoted by the preposition *at*. Examples include `face_at_link`, `link_at_face`, `links_at_node`, `patches_at_node`, and `node_at_cell`. Use of *at* tells the user that an array of element IDs is the expected return (see Fig. 4 for examples of usage). The Landlab boundary condition interface also uses *at*; for instance, `status_at_node` returns an array containing the boundary-condition status (as an integer code) of the grid nodes. All these properties return pre-allocated arrays, and can be expected to be fast.

"has", "is", and "are" methods. Use of *has*, *is*, or *are* in a method name indicates that the method in question applies a logical test to grid properties. These are not simple lookups, as in the case of *at* and *of* properties, but can still be expected to be fairly fast. The returned object will either be a Boolean, or an array of Booleans. Examples include `is_boundary`, `are_all_core`, and `has_field`.

"get" and "create" methods. Landlab's design philosophy seeks a balance between speed of access of information about the grid, and memory usage. To this end, only the most commonly used arrays of grid characteristics accessed by *at* and *of* properties are created at grid instantiation. In other cases, these arrays are allocated in memory at the first time of usage in code, then referenced from that point on at subsequent calls of the property. Methods in the grid that begin with *get* or *create* are called by these properties the first time they themselves are used, and construct the necessary arrays in memory. These methods are typically intended for call only by a well-defined subset of other methods internal to grid, and not directly by the user; i.e., in programmer's parlance they are "private". We use the standard Python practice of beginning such methods with a leading underscore in the name, which tells the various Python user interfaces not to report them in standard lists of grid methods.

Computational methods. Landlab provides a large number of grid methods to allow easy completion of common and frequently repeated analyses of the values on the grid. These are denoted by names that begin with *calc*, to denote methods that calculate a new value from provided data, or *map*, which apply some standard rule to map multiple values for connected elements to a single value on the shared element to which they connect. For instance, *calc* methods might allow calculation of gradients at links from data defined at nodes (`calc_grad_at_link`), or flux balances at a node from fluxes defined at incoming and outgoing links (`calc_flux_div_at_node`). *Map* methods might return means of values at links around nodes (`map_mean_of_links_to_node`), or minima of node values attached to each link (`map_min_of_link_nodes_to_link`), or the maximum slope of links leaving each node (`map_downwind_node_link_max_to_node`). More complex mapping schemes are also available, to allow for instance the mapping of data from topographically upwind or downwind elements only (for example,

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`map_value_at_upwind_node_link_max_to_node`). All these methods require active calculation and memory allocation of new values.

Boundary condition control. Grid methods that allow user control of boundary conditions use the word "*set*". Boundary condition handling is described further in Section 3.1.4, below.

General rules. Words are separated by single underscores. Nouns are typically singular, both describing the element and its characteristic, e.g., `area_of_cell`, not `areas_of_cells`. The exceptions are cases in which more than one thing is associated with each element, such as `links_at_node`, `faces_at_cell`. Any grid property can be expected to be a fast lookup operation if called repeatedly; methods may require additional memory allocation.

3.1.4 Grid boundary condition handling

Also provided are methods to facilitate boundary condition handling (Fig. 5). Nodes can have one of four boundary condition types: *fixed value* (Dirichlet), *fixed gradient* (Neumann), *looped*, or *closed*. A node that is not defined as a boundary is known as a *core* node. The boundary conditions defined on the nodes determine whether each connecting link is *active* (allows flux along it), *fixed* (allows flux, but flux value is fixed) or *inactive* (flux is forbidden), as shown in Table 4a. Each of these boundary conditions is associated with an integer value, which can be seen in the boundary condition arrays `grid.status_at_node` and `grid.status_at_link` (Table 4b).

We should emphasise that this framework is provided for user's convenience; it can be easily ignored if a user wishes to implement a different scheme for boundary condition handling. Further, the appropriate boundary conditions depend on the physical scenario that the user is modeling.

The edges of a Landlab grid are always defined by boundary nodes. Because perimeter nodes lack cells (Section 3.1.1), this means not every boundary node necessarily has a cell, and may also not have the standard number of links, patches, etc. (Table 1b). Conversely, any core node can always be expected to have a cell and a standard connectivity as described in that table. Likewise, inactive links at the grid perimeter lack faces, but each active link always intersects, and is uniquely associated with, a single face (Fig. 5). Thus cells share the boundary conditions of nodes (core vs. boundary) and faces share the boundary conditions of links (active vs. inactive). Note also that nodes that are in the interior of a grid (i.e. not perimeter nodes) can also be assigned as boundary nodes, and that whether or not this occurs depends on the shape of the area that the user is modeling. For example, a user may wish use a grid that represents a drainage basin, with the basin's interior consisting of core nodes, a single node representing the outlet (flagged as a fixed-value or fixed-gradient boundary), and the remainder of the nodes flagged as closed boundaries.

The grid itself is responsible for keeping track of and ensuring internal consistency between boundary condition properties. The standard numpy setters and getters are overridden for the boundary condition data structures to ensure this internal consistency without the user's involvement. For example, if a user changes a node's status from core to fixed-value boundary, the gridding engine will automatically update the status of the relevant links.

3.2 Spatially distributed data and data fields

A key element of any model of surface processes is a description of how the state variables and surface characteristics vary across the domain. Such data can include both scalar measurements at a point or over an area (such as topographic elevation, water depth, sediment cover fraction, vegetation type), and directional vector data, for instance, describing fluxes across the surface or gradients in scalar values. Landlab uses data constructs called *data fields* within the grid to store and handle this information.

A prominent advantage of the field system is that data may be associated with any of the grid elements: node, cell, link, face, patch, or corner. Data fields are one-dimensional numpy arrays whose length matches the number of elements in question. By indexing these arrays with the IDs of element subsets, the values at specific locations and on each element type can be recovered. This scheme readily allows the storage of both scalar and vector data by exploiting the geometric relationships between the node-link-patch (and cell-face-corner, if desired) groupings, as in a traditional staggered-grid scheme (Harlow and Welch, 1965; Slingerland et al., 1994). Scalar data can be stored at nodes. Because links describe the connectivity between nodes, vector information describing fluxes or gradients between nodes is readily stored on links; the link's orientation provides an implied unit vector, while the associated value represents the vector's magnitude. There are also a number of use cases in which values can usefully be stored on patches, for instance, in representing resolved means of vector values at the bounding links. This data structure also lends itself to the implementation of some cellular automata. For instance, pairwise transition automata (Narteau et al., 2001; 2009) represent the states of cells on a grid as paired "doublets", with rules prescribed to govern the rates of transition between each doublet type. These are readily implemented in Landlab by mapping the pair states onto the links of a Landlab grid, and representing the corresponding automaton cell states at grid nodes (Tucker et al., 2016).

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In terms of implementation in the code, Landlab fields are represented as a dictionary of Python dictionaries within the grid object. The keys to the first dictionary are strings of the names of the grid elements (*viz.*, 'node', 'link', 'patch', 'cell', 'face', 'corner'); the keys to the dictionaries that these return are Landlab *field names*. Users are free to create field names as they wish. However, Landlab maintains a standard format and name list which is widely used by the Landlab component library (supplemental Table S1), and users are strongly encouraged to adopt this scheme to enhance standardization and interoperability throughout the software. Our standard naming scheme echoes that of the community standards adopted by the Community Surface Dynamics Modeling System (CSDMS). Our rationale follows theirs, aiming to remove ambiguity in the identification of different types of numerical information (Peckham, 2014; Peckham et al., 2013). However, given the potential for high frequency of name usage in Landlab code, and our ability to easily assess potential ambiguities between different components, we place more value on name brevity at the expense of total unambiguity as compared with the formal CSDMS Standard Names (https://csdms.colorado.edu/wiki/CSN_Searchable_List). Nonetheless, we maintain one-to-one mappings with the CSDMS Standard Names to enable automated implementation of the CSDMS Basic Model Interface (BMI; see Section 3.4.1).

The general format for Landlab names is “thing_described__quantity_described”. This approach is more generally known as the object-attribute-value paradigm: the first word or phrase describes the object, the second word or phrase describes the attribute, and the variable’s content is its value. A double underscore separates the object from the attribute. An example might be “surface_water__discharge”. A full list of names used in Landlab components as of version 1.0 can be found in the supplementary material as Table S1. A version of this list up to date with the current release version can be found on the Landlab website.

Units can be attached to grid fields. They are recorded in a further dictionary-like structure, which is a property of the element container. This means they can be accessed with syntax like `grid[‘node’].units[‘field__name’]`.

Landlab offers some degree of “syntactic sugar” for its field name interface – i.e., the field interface is made more user-friendly by the addition of more readable grid properties to query the fields at each element type, rather than requiring the user to access the both dictionaries directly. For instance, `grid.at_node[‘my_field_name’]` is equivalent to `grid[‘node’][‘my_field_name’]`. In addition, Landlab also provides convenient shortcuts to create new fields of ones (`grid.add_ones`), zeros (`grid.add_zeros`), and from existing data (`grid.add_field`).

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3.3 Components

Components are Python objects that simulate processes within Landlab. A typical Landlab component provides a numerical representation of a single process. For instance, a component might compute the flow of water across a terrain surface using a particular flow law and numerical solution method. Components also exist in Landlab that produce only spatially invariant time series, or that produce time-invariant steady-state solutions across a surface. A prominent example would be the FlowRouter component, which calculates the steady-state accumulation of water discharge and upstream total

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drainage area through a drainage basin. The latter category also includes a number of analytical tools that produce spatial statistics for a surface; for example, components to calculate the steepness (Wobus et al., 2006) or Chi index (Perron and Royden, 2012) for a channel network.

Multiple components can be used together, allowing the simulation of multiple processes acting on a single grid. For example, components simulating hillslope processes and fluvial geomorphic processes can be easily implemented together to create a "custom" landscape evolution model. In some cases, the output from one component may form the input to another, as for example when combining flow routing and sediment transport components, or soil moisture and vegetation growth components. The design of each component is intended to work in a "plug-and-play" fashion, where each component couples simply and quickly to others. This is permitted by a standardized interface for each component, as described in Section 3.3.1. Examples of coupled component systems can be seen in Section 5.

Landlab provides a suite of existing components that can be deployed by users. Future versions of Landlab will add further components designed by the core development team. However, we anticipate that users of Landlab will also devise new components of their own, allowing the exploration of new processes within Landlab. In keeping with the open source ethos of the project, we would encourage such users to in turn commit their work back to the master fork of Landlab, for the use of others. Documentation and advice for this process can be found on the Landlab website.

3.3.1 Component standard interface

Landlab components have standardized interfaces, which are designed to enhance interoperability both internally to Landlab (between components, or between components and Landlab utilities) and between Landlab and external interfaces like the CSDMS Basic Model Interface (Peckham et al., 2013) (see also Section 3.4.1). The Landlab standardized component interface consists of the following:

- An initialization method, with the standard argument signature `__init__(self, grid, x=a, y=b, z=c, ..., **kwds)`, where *grid* is a Landlab grid object, *x*, *y*, and *z* are component-specific keyword arguments with default values *a*, *b*, and *c*, and ***kwds* is an optional keyword argument dictionary. The grid object passed during instantiation is accessed during the running of the component, and its data fields are updated automatically. A component may have any number of component-specific keyword arguments. The variable names of these arguments are not standardized, but rather are generally unique to each component. The component-specific arguments are, however, required to have default values. The names of the keyword arguments make explicit the data requirements of the component in order to run. However, the ***kwds* argument alternatively allows these parameters to be set from a dictionary of model parameters. In other words, this component could be initialized in two equivalent ways:

```
>>> ld = LinearDiffuser(grid, linear_diffusivity=1.0, method='simple')
```

or

```
>>> paramdict = {'linear_diffusivity': 1.0, 'method': 'simple'}
>>> ld = LinearDiffusivity(grid, **paramdict)
```

- A run method, with the standard argument signature `run_one_step(dt, *args, **kwds)`, where *dt* is an interval of time over which to execute the component before returning a result, and **args* and ***kwds* are an argument list and dictionary respectively, specific to each component. These latter items allow any additional arguments necessary for the model to run to be passed in. If *dt* is not required for a component to run, it may be omitted.
- A standard set of properties for the component: *name*, *input_var_names*, *output_var_names*, *var_units*, *var_mapping*, and *var_definition*. These properties describe the fields that the component interacts with, the units of each, which element each field is defined on, and a brief summary of what each field represents.

All components inherit from the base class *Component*. This base class enables and regulates the standardized properties and interface that are available for every Landlab component. It also provides methods designed to streamline the creation of the output data fields when a component is instantiated.

Landlab version 1.0 provides a standard component library as part of its installation. A full list of components available in version 1.0 can be found in Table 5. Although these existing components are largely Earth-surface focused, we emphasize that Landlab permits modeling of the evolution of almost any two-dimensional system that lends itself to description by discretized systems of differential equations or cellular automaton rules.

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3.3.2 Timestepping and interaction of components

For most existing Landlab components, the component is responsible for controlling its own internal numerical stability. A timestep parameter *dt* is passed to each component that operates in a time-dependent fashion; this timestep can be thought of as the "coupling timescale", and represents the frequency of interaction between components if more than one is coupled (Fig. 6). However, it is not necessarily the stable timescale, which will vary between components. Each component is responsible for calculating its own stable timestep under the model run conditions, and internally subdividing the imposed *dt* in order to ensure the model run does not become unstable. The user is responsible for selecting an appropriate coupling timescale – too short, and a model run will take more steps than necessary for each component to be stable; too large, and information transfer between the components will be limited, possibly introducing an additional source of numerical error.

Note also that where components employ implicit solutions, there may be no internal limit to the timestep at all (e.g., Braun and Willett's (2013) Fastscape algorithms for stream power). In such cases, Landlab will make no check on the imposed timestep, and the user must ensure that the imposed *dt* is appropriate under the boundary and initial conditions that they are running. For instance, the Braun-Willett algorithm ceases to behave in a truly timestep-independent fashion under transient conditions, but in a way that still permits timesteps larger than would be imposed under an explicit Courant condition (for more details see their Appendix B). However, those authors did not propose an alternative scheme to limit the timestep in such cases, and consequently Landlab also does not. A user of this component is assumed to have read the component documentation and taken on board that this is potentially an issue, and to have taken steps to check that their output is behaving sensibly and is not highly sensitive to changes in the supplied timestep. We reiterate that it is ultimately the user's responsibility to check that the provided *dt* is appropriate to the modelling scenario in hand.

3.3.3 Parallelization

Together, the componentized nature of Landlab and the level of flexibility afforded to the user conspire to rule out the idea of Landlab as a whole being highly optimized through parallelization. However, there is great potential for parallelization of Landlab at the component level, since the run methods of each component are entirely self-contained. As proof of concept, the Flexure component has already been parallelized (see online code and documentation). Although in Landlab version 1.0 we have not had a compelling enough use case to invest significant time in such work, many of the components already in the library would be amenable to parallelization in this style, and this could be done in future releases.

3.4 Utilities and interfaces

In addition to the grid, which governs the topology and connectivity of spatial data, and the components, which describe how spatial data change with time, Landlab also offers tools that control input and output, including data input and export, translation between widely used data formats, plotting, and the BMI external model interface. Landlab can read and write data files in NetCDF4, VTK, and ESRI ASCII data formats. These options are intended to allow interoperability with third-party software, especially Geographical Information Systems, and also to allow Landlab data to be manipulated in and displayed with specialized visualization software (such as ParaView).

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Landlab's standard interfaces also allow it to interact more easily with software frameworks developed by the geoscience and hydroscience communities. For instance, Landlab is already embedded within the Hydroshare collaboration environment, http://www.hydroshare.org. This means that Landlab models can be created and run within the Hydroshare data and modelling environment, and can take advantage of that environment's shared data platform and metadata systems.

3.4.1 Dynamic model interaction and the Basic Model Interface

As noted in previous sections, Landlab has been designed from conception to be fully compliant with the Community Surface Dynamics Modelling System's Basic Model Interface (BMI) (Peckham et al., 2013). The BMI concept allows any two models describing the changes caused by surface processes to be coupled together, regardless of the vagaries of model gridding schemes, programming languages, or other low-level design choices. It does this by means of a standard interface (the Basic Model Interface, *sensu stricto*), which is callable for any BMI compliant model or component and includes generically applicable functions such as `initialize`, `update` (i.e., run one timestep), and `get_current_time`. The interface allows information about the current state of a simulation to be passed back and forth between running models in a manner that is agnostic in terms of implementation details.

The Landlab framework is designed such that the Landlab standard component interface can also expose a full BMI interface; in other words, *all Landlab components are also BMI-compliant components*. This means that by choosing Landlab as their model development environment, users also gain the ability to couple their models immediately with any other model in the CSDMS repository of BMI-compliant codes. This choice will also enhance the utility of Landlab to users who wish to implement component functionality alongside some other model using the CSDMS BMI or Web Modeling Tool (WMT) (Piper et al., 2015).

4. Validation, testing, and documentation

Landlab makes extensive use of Python's native documentation and code testing systems in order to test and validate the code base and to keep our documentation up to date. The development team exploits a combination of this Python "doctesting" and unit testing techniques to simultaneously test and document the code base. Doctests are code examples that can be included in the docstring that describes each Python method, and they list the expected output from each line of code as part of the documentation. Crucially, this code is then actually run whenever testing of the code base is triggered (for instance, by calling `landlab.test()`), and any doctests for which the output does not match the expected solution are recorded as either an error (tested function does not run cleanly) or a fail (output does not match). Because doctests are part of each function's docstring, they are also then automatically scraped from the code and included in the online documentation as examples for the user. In this way doctests allow us both to help ensure Landlab functionality does not break as the code base evolves, while at the same time documenting for the user the way in which a given method, function, property, or component can be used.

Landlab also includes suites of unit tests. These are test scripts written specifically to exercise particular aspects of the code, and to check the output of that test against known correct solutions. Examples of when this is useful can occur in longer or more involved code, especially in components, where various different configurations of grid types and initial and boundary conditions need to be tested to ensure the component is robust under various different conditions. Unit tests differ from doctests in that they are not intended to be user-facing, although they are run alongside them when testing of the code base is triggered.

Almost all core Landlab functionality of both grid methods and components is now tested in this way. As of this version, around 1400 separate tests are run on the code each time testing is triggered, and the tests cover 80% of the code base. Most of the remaining uncovered code is either challenging to adequately test (for example, plotting functions), not part of the core Landlab functionality (such as helper scripts involved in building releases), or deprecated. Tests are triggered automatically and remotely through the web-based applications Travis (Mac/Linux) and Appveyor (PC) whenever a new commit is made to either a branch or the master version of the code repository on GitHub, or when a new release of the code is built. These tests are performed on a range of supported Python versions, including both versions 2 and 3. Tests can also be triggered manually on a local machine by running a testing script included with Landlab, or by calling `landlab.test()` from an interactive Python environment.

5. Creating models with Landlab

We here illustrate some of the key functionality of Landlab by example, demonstrating its applicability across a variety of types of problem. We hope to emphasize here that Landlab *is not a landscape evolution model* (although it can be used to create them) – rather, it presents a framework under which a wide variety of different models can be implemented using its tools, including hydrologic, ecologic, and sedimentological models, as well as landscape evolution models. This section illustrates four possible contrasting model designs that can be implemented within the Landlab framework: a very simple "toy" geomorphic diffusion code that demonstrates the core functionality of the grid; a coupled stream power-hillslope diffusion model driven with a stochastic sequence of storms, illustrating some of Landlab's components; a cellular automaton, demonstrating a fundamentally different style of model implementation that is also enabled by Landlab's design; and a flood wave routing model, run on real topographic data ingested by Landlab. We hope that these examples will also serve as an illustration of the potential power of the Landlab framework to enable novel or under-explored process interaction studies (e.g., of vegetation on landscape evolution; of surface hydrology on stochastic surface processes).

5.1 A simple diffusion model

Although Landlab provides "off the shelf" process simulation code in the form of the components, Landlab also facilitates the design of models without using the components. The Landlab grids provide mapping, gradient, and divergence functions to make implementation of, for instance, finite-difference or finite-volume methods both concise and straightforward.

Here we illustrate this functionality using a simple finite-volume diffusion scheme, which here is representing the down-slope flow of soil on hillslopes (Culling, 1963). We wish to represent the evolving form of a diffusional hillslope that is undergoing a constant uplift (1 mm y^{-1}) with reference to a relative base level. In this case, the grid is radial and so roughly circular in plan view. Use of this particular configuration is intended in part to demonstrate the flexibility of Landlab's design, although this radial grid arrangement could perhaps be thought of in terms of response to a rising volcanic mound or salt diapir, or other similar scenario with a radially symmetric uplift field.

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The governing equations for this example are:

$$\frac{\partial \eta}{\partial t} = U - \nabla q_s \tag{1}$$

$$q_s = -D \nabla \eta \tag{2}$$

where η is land-surface elevation, t is time, U is the rate of vertical motion ("uplift") of rock relative to base level, q_s is volumetric sediment flux per unit slope width, and D is a transport coefficient with dimensions of length squared per time.

For our example model, Eq. (2) will be discretized and solved using a finite-volume solution scheme. Consider a cell of surface area a that is surrounded by N neighbouring cells (Fig. 7). We can integrate Eq. (1) over the surface area of the cell:

$$\int_a \frac{\partial \eta}{\partial t} da = \int_a U da - \int_a \nabla q_s da \tag{3}$$

Applying the divergence theorem to the last term on the right, and evaluating the other two integrals,

$$a\frac{\partial\bar{\eta}}{\partial t} = Ua - \oint_p q_s(p)\,\mathbf{n}dp \tag{4}$$

where $\bar{\eta}$ is the average elevation within the cell, *p* represents position along the perimeter of the cell, and $\mathbf{n}$ is a unit vector normal to the perimeter and pointing outward. The last term is a line integral that represents adding up all the inflows and outflows of mass along the cell's perimeter. If the cell is a polygon with *N* faces, this last term can be replaced by a summation:

$$\frac{\partial\bar{\eta}}{\partial t} = U - \frac{1}{a}\sum_{\boldsymbol{k=1}}^{\boldsymbol{N}} q_{sk}w_k \tag{5}$$

where q_{sk} is the unit flux at face *k*, positive outward, and w_k is the width of face *k*.

We will implement this solution in Landlab by assigning to each node *i* the value of the average elevation within its cell, $\bar{\eta}_i$ (for notational convenience, we will drop the use of the overbar below). To calculate the flux at each face, we first need to calculate the topographic gradient at each face. We will do this by taking the elevation difference between each neighboring pair of nodes, dividing by the length of the link that connects them, and then assigning the resulting gradient value to the relevant link. The gradient at link *j* is therefore calculated as:

$$G_j = \frac{\eta_{H_j} - \eta_{T_j}}{L_j} \tag{6}$$

where η_{H_j} and η_{T_j} are the elevation values at link *j*'s head and tail nodes, respectively, and L_j is the length of link *j*. In Landlab's gridding engine, the calculation of link-based gradients in a node-based scalar quantity like η is handled by the grid method `calc_grad_at_link`, which takes a node array or field name as an argument and returns a link array. Figure 7 illustrates how values of η defined at nodes can be used to calculate gradients at links, and then the gradients can be used to calculate the net flux into and out of a cell.

In our diffusion example, the summation of fluxes along the cell faces is calculated as follows:

$$\sum_{k=1}^{N} q_{sk} w_k = \frac{D}{a_i} \sum_{k=1}^{N} \delta_{ik} G_k w_k \tag{7}$$

where δ_{ik} indicates the direction of link k relative to the cell i: if δ_{ik} = -1, the link points outward from the cell; if δ_{ik} = +1, the link points inward.

To calculate flux divergence using this finite-volume approach, Landlab provides the general grid method `calc_flux_div_at_node`, which takes a link-based array of unit fluxes as an input, and returns a node array that contains the sum of in/out fluxes (divided by cell area) at each node (Fig. 7). Values at perimeter nodes, which lack cells, are ignored. In keeping with the standard definition of the divergence operation, the function returns positive values where the net flux is outward, and negative values where it is inward.

In the diffusion example shown in Figure 8, the time derivative is discretized using a simple forward-Euler explicit method, such that the values of elevation at the new timestep t+1 are calculated from values at the old timestep:

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$$\eta_i^{t+1} = \eta_i^t + \Delta t \left[U + \frac{D}{a_i} \sum_{k=1}^{N} \delta_{ik} G_k w_k \right] \tag{8}$$

where the superscript indicates timestep, and the quantity in brackets is evaluated at timestep t. The code to implement the model is shown in Figure 8. Note the use of the `calc_grad_at_link` and `calc_flux_div_at_node` methods (and note also that U = 0 in this example).

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An advantage of the finite-volume approach is that it can be applied to cells of any shape. For instance, it can be used with hexagonal cells, or with Voronoi polygons as in the example in Figure 8.

This model can be implemented in Landlab and plotted in as few as 16 lines of code (Fig. 8). Here, line 1 imports the Landlab classes and functions we will use, and line 2 imports the `show()` function from matplotlib that will let us display the plot. Line 3 instantiates the Landlab grid object. This example uses a RadialModelGrid, but the same code would work with any grid type. Lines 4–6 initialize data for the model run. z will be the land surface elevation at each node; qs will be the volumetric sediment flux per unit width along each link. Note that this implementation is consciously not using data stored as Landlab fields, to illustrate that this is not a requirement; however, it would be trivial to modify lines 4 and 5 to create the data as fields on the grid, and the remainder of this script would be unchanged. Line 7 is the first line that actually begins the calculations that perform the diffusion. This line calculates a Courant-Friedrichs-Lewy (CFL) stability condition (Slingerland and Kump, 2011) for the maximum stable timestep for the finite-volume scheme we are about to implement.

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Lines 8–14 implement a time loop, within which the diffusion occurs. The core (i.e., interior) nodes of the grid are uplifted at a rate of 0.001 length units per time unit relative to base level. Lines 10–14 implement the meat of the differencing scheme, where we use a staggered grid to solve the discretized diffusion equation (Eq. 8). The depth-integrated fluxes on the links are calculated as the product of the diffusivity parameter *D* and the topographic gradient at the links (lines 10, 11), taking care to calculate the flux only on active links. The flux divergence is then calculated at each node based on the fluxes on the links to which is it adjoined (line 12). Note that Landlab enables each of these operations to be performed with a single grid method. The final lines of the code invoke the standard Landlab plotter, then display the output. Although we have not specified any particular units in our calculation, in line 15 we assert that the length unit is meters and the time unit is years.

Note that this same result could have been achieved even more concisely using Landlab’s inbuilt LinearDiffuser component. The equivalent code is shown in Fig. 9. Not only are the implementation details of the scheme now handled entirely within the component, but so also is internal subdivision of the provided timestep to meet the necessary stability conditions for the simulation. Additionally, the elevation data are now passed into the component as the field ‘topographic__elevation’ – which is attached to the grid – rather than as a separate variable (lines 5, 7), as discussed in Section 3.2.

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5.2 Coupling diffusion to stream power with a storm sequence

The next example illustrates a simple model for the evolution of an eroding and uplifting landscape, explicitly representing channel incision and hillslope processes. In this model, we also explicitly represent time variability of water input to the system (i.e., storms). In technical terms, the example is designed to show in more detail the use and coupling of several Landlab components: the FlowRouter, the StreamPowerEroder, the DepressionFinderAndRouter, the LinearDiffuser, and the PrecipitationDistribution classes. The aim here is to demonstrate how Landlab couples components, and to illustrate several different component styles.

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Here, channel incision processes are represented by the stream power law (Howard, 1994; Lague, 2014; Whipple and Tucker, 1999), which says that incision rate, *E*, of a stream is proportional to a product of powers of channel discharge, *Q*, and local channel bed slope, *S*. In this version, we also include an incision threshold, *C*, below which incision is forbidden:

$$
\begin{array}{ll}
E = K\,Q^m\,S^n - C & \text{if } C < K\,Q^m\,S^n \\
E = 0 & \text{if } C >= K\,Q^m\,S^n
\end{array}
\tag{9}
$$

In this case m = 0.5, K = 1e-5 $m^{-0.5}y^{-0.5}$, C = 1e-5 m y^{-1}, which are fairly typical and widely-adopted values for a generic erosional upland landscape (Harel et al., 2016; Tucker and Whipple, 2002). Here we also adopt n = 1. This is primarily to maintain dimensionally sensible units for K while still honouring the widely-observed ratio of m/n ~ 0.5, interpreted from channel concavities of natural rivers at apparent topographic steady state. Nonetheless, we note n > 1 in some global data compilations for stream power where C = 0, and suggest our incorporation of an explicit erosion threshold makes our choice of n = 1 reasonable (Harel et al., 2016). We shall see that this set of values together produce a plausible total landscape relief of order 1 km for catchments of maximum length ~5 km, which is within the range expected for real catchments of this scale in tectonically active regions. Other forms of stream power-based incision rules are also possible using this component, but are not illustrated here.

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The Landlab StreamPowerEroder and FlowRouter components deployed here use the “Fastscape” algorithms of Braun and Willett (2013). This solution scheme is implicit and order-n, and permits arbitrarily long, numerically stable timesteps to be taken. The Fastscape algorithm requires out-of-order (i.e., upstream order) iteration through the nodes, but pure Python code has relatively poor speed performance when executing explicit loops or iterations through arrays. For this reason, both the stream power and flow routing components also use compiled Cython (see Section 2.2) to accelerate these speed bottlenecks in the code. (The release version of Landlab distributes this code in pre-compiled form to users.) The run method of the component performs as order-n, and as expected is unaffected by grid type (in this demonstration, raster versus hex grids). The initialization of the grid and components adds a very small overhead which also increases close-to linearly with grid size (Fig. 10; code in supplementary information as Script S2). This overhead reflects the calculations necessary to build the data structures describing the grid’s connectivity, and is significantly greater for Voronoi grids compared to rasters, due to the iterative calculations required to assemble Voronoi grid-connectivity arrays.

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The final topographies from the raster and hexagonal implementations of this pure stream power component are shown in Fig. 11. The code can be seen in the supplemental information as Script S3. It conforms to a typical form for a Landlab driver script, which looks like:

1. Import necessary Python libraries, including from Landlab
2. Instantiate a grid object
3. Create input fields and set the grid initial and boundary conditions
4. Instantiate the components

5. Perform a loop to run the components
6. Finalize, plot, save, and/or export

In this case, the model is driven by a stochastic storm generator (the PrecipitationDistribution class), based on that suggested by Eagleson (1978) and similar to the one underlying the CHILD landscape evolution model (Tucker and Bras, 2000; Tucker et al., 2001b). Unlike CHILD but in keeping with Eagleson's original derivation, here an explicit inverse relationship between storm length and intensity is built into the distribution, by calculating storm water depth as a gamma-distributed random variable, and then deriving storm intensity as the quotient of depth and (exponentially distributed) duration. This approach prevents unrealistic long-duration, high-intensity events from being sampled (Eagleson, 1978). The PrecipitationDistribution class provides a method that yields tuples of interval durations and rainfall intensities as a true Python generator – in other words, the code block below the generator will repeat with fresh values for each iteration until the total time is elapsed, at which point the loop will cease (see lines 46–53 in the code). This makes the implementation of the "run" loop both efficient and concise, as well as being a classically "Pythonic" way to implement this kind of loop. In this instance, the parameters for the PrecipitationDistribution have been chosen to represent a mean annual rainfall rate of around 5 m y^{-1}, and with rainfall occurring around 10 % of the time.

Deleted: fresh values are returned each time the method is looped upon, until such time as the total elapsed time exceeds the supplied run time,

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The switch between grid types involves changing a single line of code (see the logical test at lines 15–18). Note that although the total number of nodes and the number of rows and columns is identical in both cases, the hexagonal grid is rectangular rather than square due to the single axis of mirror symmetry present in a tessellation of regular hexagons. (The HexModelGrid class provides flags allowing control both of the orientation of this symmetry axis, and also the shape of the perimeter of the grid – rectangular or hexagonal.)

The addition of the linear diffusion component, LinearDiffuser, is performed simply by creating an instance that class, then incorporating its run method into the loop (code S4, lines 40 and 49). As in previous examples, each component is responsible for managing its own internal numerical stability – in this case, if the LinearDiffuser run method receives an input *dt* that exceeds the Courant-Friedrichs-Lewy stability limit, that timestep will be internally subdivided as necessary within the component.

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In this example, because diffusion can occur independently of stream incision, it is possible that diffusion can sever the flow paths of the FlowRouter and create internal basins. Because of this possibility, this version of the code also includes a lake-filling algorithm, implemented as the component DepressionFinderAndRouter. The lake-filling algorithm identifies closed depressions in the topography then reroutes flow across them, and is based on the algorithm of Tucker et al. (2001b). The final topography of the coupled stream power and linear diffusion model is shown in Fig. 12.

5.3 Landlab as a cellular automaton

Much of this manuscript focuses on Landlab as a tool for the implementation of numerical solutions to two-dimensional partial differential equations, as many geomorphic process laws (sensu Dietrich et al., 2003) have been couched in the language of differential equations. However, Landlab can also act as a powerful environment for the implementation of cellular models. Landlab provides a set of tools for the construction of “continuous-time stochastic” (CTS) cellular automata (CA). This interface within the main body of Landlab is known as CellLab-CTS (Tucker et al., 2016). It enables efficient creation of CTS models: a user needs only to specify the states and transition rules, and write a short Python script to initialize and run a CellLabCTSModel object. Figure 13 shows output from a CellLab-CTS model implementing a lattice-grain algorithm (Tucker et al., 2016).

Landlab can also be used to construct traditional discrete-timestep cellular automata. An example is provided by developing an ecohydrology model in Landlab (Fig. 14a, code S5), which is in part an implementation of the Cellular Automata Tree-Grass-Shrub Simulator (CATGraSS) (Caracciolo et al., 2016a; 2016b; 2014; Zhou et al., 2013). CATGraSS couples local vegetation dynamics, which simulate biomass production based on local soil moisture and potential evapotranspiration, and plant establishment and mortality based on competition for resources and space at each cell of a gridded model domain. Each cell in the domain can be occupied by one Plant Functional Type (PFT): each cell is flagged as Tree, Shrub, Grass or Bare (left unoccupied).

CATGraSS is driven by rainfall pulses and solar radiation. In Landlab, the model is implemented as a set of interacting components, each of which describes a different element of the coupled system: PrecipitationDistribution, Radiation, PotentialEvapotranspiration, SoilMoisture, Vegetation, and VegCA. This means that each process can also operate in isolation, outside the context of this example model. The PrecipitationDistribution component simulates the random arrival of storm pulses. Precipitation characteristics are based on the seasonal rainfall statistics of a region and characterized by exponential distributions of storm and inter-storm duration, and a gamma distribution of water depth as a function of storm duration. Storm pulses recharge the soil moisture storage, represented as a single bucket (Laio et al., 2001). The Radiation component calculates daily average extra-terrestrial and clear-sky shortwave radiation incident on a flat surface, based on latitude and day of the year (ASCE-EWRI, 2005). This component also calculates daily radiation ratio, defined as the ratio of cosine of solar angle of incidence for the true sloped surface to that for a flat surface (Bras, 1990). The Radiation component does not explicitly calculate diffused and reflected radiation. The PotentialEvapotranspiration component uses the radiation ratio to calculate spatial net radiation using daily maximum and minimum temperature, and potential evapotranspiration (ASCE-EWRI, 2005; Zhou et al., 2013). The SoilMoisture component models local root-zone soil moisture dynamics depending on the PFT that occupies the corresponding cell at a given time (Laio et al., 2001). The Vegetation component simulates temporal dynamics of above-ground live and dead biomass, as well as Leaf Area Index

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Deleted: The Radiation component calculates the ratio of total incoming shortwave radiation on each cell in the domain with respect to a flat surface, assuming homogenous cloud cover, based on local slope and aspect (Bras, 1990). This ratio is used to spatially distribute potential evapotranspiration calculated by the PotentialEvapotranspiration component

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(LAI). It does this by computing Net Primary Productivity (NPP) based on the concept of water-use efficiency (WUE) that relates NPP to actual evapotranspiration (ET) and vegetation foliage loss due to water stress and senescence (Istanbulluoglu et al., 2012; Zhou et al., 2013). The VegCA component handles the spatial organization of PFTs, through plant establishment, competition, and mortality, by combining deterministic and probabilistic rules. Plant establishment is driven by seed dispersal and water stress, while mortality is related to water stress, plant age, and disturbances (Zhou et al., 2013).

This example ecohydrology model and its constituent components can work both on grids imported from a Digital Elevation Model (DEM) using the `read_esri_ascii` utility (see also Section 5.4), and on synthetic grids created using the RasterModelGrid library. In the example illustrated in Figs. 14b and 14c, we use the example ecohydrology model (code S5) to simulate plant competition in a semi-arid basin in Sevilleta, New Mexico, USA, modelling the plant species found in this area (Zhou et al., 2013). Because of the stochastic nature of the simulations in this example, potential evapotranspiration is represented by a sinusoidal function of day of the year (Zhou et al., 2013). The domain is initialized with randomly assigned PFTs with random spatial distribution of ages (Fig. 14c(i)). All PFTs initially have an identical cover fraction in the domain. Local vegetation dynamics are simulated at inter-storm timesteps, and plant competition is modeled at annual timesteps. In the simulations, trees are outcompeted by drought-tolerant shrubs and grasses in the first few hundred years, consistent with regional observations in central New Mexico (Zhou et al., 2013). Shrubs and grasses coexist in the modeled domain with alternating periods of shrub and grass dominance. Note that shrubs cluster as they propagate in space due to seed dispersal from mature shrub plants.

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5.4 Landlab as a hydrological modelling environment

Landlab also contains several surface water flow generators, including an explicit two-dimensional solution for the shallow water equations. The OverlandFlow component has been adapted from the flood inundation model described by de Almeida et al. (2012). Their algorithm was derived for use on structured grids, and the Landlab implementation only works with the RasterModelGrid library. Water discharge is calculated on each active link within the model domain, simulating a hydrograph at each link location.

In many flood-wave routing models, a small timestep must be used to prevent instabilities, which often manifest as 'checkerboard' patterns of water depth, from emerging. To maximize computational performance of the OverlandFlow component, an adaptive timestep is used to find the largest timestep that adheres to the CFL stability condition (Hunter et al., 2005). To further enhance the stability, the OverlandFlow component also contains stability criteria so that the component can operate not only on low-slope urban areas, but also steeper terrain, such as mountainous watersheds (Adams et al., 2016). The OverlandFlow component was designed for structured grids, and

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it assumes water can only move in the four cardinal directions. This is easily accommodated within Landlab, and several other components (e.g., the FlowRouter, and others in the example presented below) can also be optionally instructed using keywords to only use node neighbors in these cardinal directions.

An example script running the OverlandFlow component can be seen in the supplementary information as Script S6. It follows a similar pattern to scripts outlined in earlier parts of this section, with import of the Landlab and other Python classes and functions needed, followed by grid creation, component instantiation, component execution in a loop, then finalization and plotting. Notably, this script uses an imported digital elevation model (DEM) of a real landscape over which to route flow, which is ingested into Landlab using the `read_esri_ascii` function contained in Landlab's input and output utilities. Use is made of Landlab's native boundary handling system to designate nodes of the grid outside of the irregularly-shaped catchment as closed, excluding them from the calculations.

This example combines the OverlandFlow component with the SinkFiller. The SinkFiller is run on the initial topography prior to the simulated storm, and fills any local depressions present in the surface. This has been done to enable full drainage of all the water from the network, and to permit evaluation of the full water budget at the outlet. However, in general the OverlandFlow component will happily run on landscapes that do contain pits. In this example, a rainfall rate of 25 mm h^{-1} was run over the watershed DEM for one hour. The resulting hydrograph (water discharge over time) is plotted at the outlet. Water depth across the domain is also plotted to show the wave front propagating downstream (Fig. 15). As expected, the total hydrograph duration is several times the length of the storm, and the peak in the hydrograph lags behind the storm itself significantly, in this case by more than an hour.

6. Conclusions

Landlab is an open-source, Python-based software toolkit designed to accelerate the development of new process models. It consists of a gridding engine, a set of components describing individual surface processes, and a set of utilities for data input, output, and visualization. Landlab not only permits the creation of models by combination of existing components, but is also optimized to aid in the design of new process components. The code base is thoroughly documented both online and within the code itself, and each release undergoes an automated testing procedure to ensure its robustness. A set of tutorials and examples to help learn about Landlab is also provided.

Landlab is explicitly designed to interface with other software, and in particular, with other models of surface processes. It exposes a CSDMS Basic Model Interface. It can serve as a platform to develop both continuum-based and cellular-automaton-style models, and potentially to have the two model styles interact on the same grid. We illustrate some of the functionality of Landlab and its existing components with a suite of examples drawn from geomorphology, ecology, and hydrology. The examples provided in this paper illustrate the wide diversity of scientific questions that can be addressed using Landlab-built models.

7. Code availability

This text describes Landlab version 1.0.2 (“Rapunzel”), which was released in November 2016. The source code for this version is maintained in a git repository hosted on GitHub at https://github.com/landlab/landlab/releases/tag/v1.0.2 (the latest development version of Landlab is always available at http://github.com/landlab/landlab). Landlab can also be installed as a release version, including pre-compiled binary files containing Cython extensions, through the *conda* and *pip* Python package management systems, as described in the online documentation. Documentation and installation instructions for the most current release version of Landlab are provided at http://landlab.github.io. Software dependencies are listed at https://landlab.github.io under Install. To the best of our knowledge, Landlab will operate on any system that meets these software requirements; as of the time of writing, Landlab is known to work on, and is tested for, recent-generation Mac, Linux, and Windows platforms running Python 2.7, 3.4 and 3.5. Landlab and its components are distributed under an MIT open-source license.

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Table 1a. One-to-one mappings of Landlab grid elements.

Element 1	Element 2	Behaviour at grid perimeter
Node	Cell	Perimeter nodes lack cells
Link	Face	Perimeter links lack faces
Patch	Corner	Neither element defines the perimeter

Table 1b. Primary one-to-many mappings of Landlab grid elements.

Element	Connected elements	*Number of each connected element in by grid type:*		
		Raster	**Voronoi-Delaunay**	**Hexagonal**
Node	Link, patch	1:4	Variable	1:6
Link	Node, patch	1:2	1:2	1:2
Patch	Node, link	1:4	1:3	1:3
Cell	Face, corner	1:4	Variable	1:6
Face	Cell, corner	1:2	1:2	1:2
Corner	Face, cell	1:4	1:3	1:3

Table 2. Currently implemented grid types in Landlab

Grid type	Grid parent	Notes
Base	None	The base class; a grid defining the elements but without any internal geometry or topologic connectivity imposed.
Raster	Base	Regular grid with identical, square or rectangular cells.
Rectilinear	Raster	Regular grid with quasi-rectangular cells whose size can vary across the grid.
D8 Raster	Raster	As for raster, but with diagonal connections between nodes.
D8 Rectilinear	Rectilinear	As for rectilinear, but with diagonal connections between nodes.
Voronoi-Delaunay	Base	Irregular grid with polygonal cells and triangular patches. Each node has n>=3 links.
Radial	Voronoi-Delaunay	Irregular grid where nodes form concentric, evenly spaced rings around a central node.
Hex	Voronoi-Delaunay	Regular grid with identical, regular hexagonal cells and equilateral triangle patches. Each core node has exactly 6 links.

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Table 3. Standard grid method and property naming conventions, listed in approximate order of operation speed.

Name contains	Refers to	Operation speed
at	Connectivity of grid elements	Lookup
of	Property of grid or grid element	Lookup (may require allocation on 1st use)
has, is, are	Logical test on grid property	Memory allocation
get, create	Memory allocation of grid property	Memory allocation
set	Update boundary conditions	Calculation; internal consistency checks
map	Map several pieces of data from several elements onto a single element to which they all connect	Several calculations & memory allocations
calc	Perform a calculation using data defined on grid elements	Several calculations & memory allocations

Table 4a. Link boundary condition status as dictated by node boundary condition status.

Nodes at link ends	Link status	Carries flux?
Core – Core	Active	Yes
Core – Fixed value	Active	Yes
Core – Fixed gradient	Fixed	Yes
Core – Looped	Active	Yes
Core – Closed	Inactive	No
Boundary-Boundary	Inactive	No

Table 4b. Integer values associated with each boundary condition status.

Element type	Status	Integer Value
Node	Core	0
Node	Fixed value	1
Node	Fixed gradient	2
Node	Looped	3
Node	Closed	4
Link	Active	0
Link	Fixed	2
Link	Inactive	4

Table 5. Components available in Landlab v.1.0.

Component name	Process simulated/Analysis performed	Key reference
LinearDiffuser	Linear diffusion of topography	Culling (1963)
PerronNLDiffuse	Nonlinear hillslope diffusion	Perron (2011)
Flexure	Simple lithospheric flexure under loading	Lambeck (1988), Hutton & Syvitski (2008)
gFlex	A more complex flexure model, utilizing gFlex	Wickert (2016)
FlowRouter	A convergent flow router, following the Fastscape algorithms	Braun & Willett (2013)
DepressionFinderAndRouter	A lake filler that can route flow across depressions	Tucker et al. (2001a)
SinkFiller	An algorithm to fill depressions in a surface	Tucker et al. (2001b)
OverlandFlow	A shallow overland flow approximation	de Almeida et al. (2012), Adams et al. (2016)
KinematicWaveRengers	A solution to the depth varying Manning equation for surface flow	Julien et al. (1995), Rengers et al. (2016)
SoilInfiltrationGreenAmpt	Infiltrate surface water into a soil following the Green-Ampt method	Julien et al. (1995), Rengers et al. (2016)
SoilMoisture	Compute local inter-storm water balance and root-zone soil moisture saturation fraction	Laio et al. (2001)
PotentialEvapotraspiration	Calculate potential evapotranspiration across a surface	Snyder (2005), Zhou et al. (2013)
Radiation	Calculate total incident shortwave solar radiation	Bras (1990)
Vegetation	Calculate above-ground live and dead biomass, and Leaf Area Index	Istanbulluoglu et al. (2012), Zhou et al. (2013)
VegCA	Cellular Automata algorithm to simulate spatial organisation of PFTs	Zhou et al. (2013)
PrecipitationDistribution	Generate a storm sequence of intervals and intensities	Eagleson (1978)
FireGenerator	Produces intervals between fire events, following a Weibull distribution	Polakow & Dunne (1999)
StreamPowerEroder	Implements fluvial erosion according to stream power, using the Fastscape algorithms	Braun & Willett (2013)
FastscapeEroder	An alternative implementation of the Fastscape stream power algorithms	Braun & Willett (2013)
DetachmentLtdErosion	An implementation of stream power erosion *not* based on Fastscape	Howard (1994)
SedDepEroder	Sediment-flux dependent shear stress based fluvial incision	Hobley et al. (2011)
SteepnessFinder	Calculates steepness indices for a channel network	Wobus et al. (2006)
ChiFinder	Calculates the chi index along a channel network	Perron & Royden (2012)

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Figure captions:

Figure 1: Examples of surface-process models. (a) Computed depth-to-groundwater, from the GSEM coupled groundwater-surface water model (Berger, 2000, image courtesy D. Entekhabi). (b) Computed patterns of soil erosion and sedimentation on agricultural fields, using the SIMWE soil erosion model (Mitas and Mitasova, 1998). (c) Model of ice-age glacier extent over the Sierra Nevada Mountains, using the GC2D iceflow model (Kessler et al., 2006). (d) Simulation of canyon erosion and fan-delta progradation in a region of active uplift (top) and subsidence (bottom), using the CHILD landscape evolution model (Tucker and Hancock, 2010). (e) Model of simultaneous cratering and fluvial erosion on the ancient Mars surface, with the MARSSIM model (Howard, 2007). (f) Simulation of pyroclastic flows at Tungurahua volcano, Ecuador, using the VolcFlow model (Kelfoun et al., 2009).

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Figure 2: Schematic illustration of the structure of Landlab 1.0. The three main divisions of the code are the grid, the components, and supporting utilities. Structure within these three main divisions is discussed in the main text.

Figure 3: Geometry and topology of grid elements on various Landlab grids. Only one patch and its bounding links are shown for each example to prevent the diagram from becoming cluttered. Links always point into the upper right semicircle, as described in the text.

Figure 4: Standard ordering schemes and conventions in Landlab. Examples are shown for both a small RasterModelGrid (a) and a small VoronoiDelaunayGrid (b). Point elements (nodes, corners) are numbered in black plain text, areas (patches, cells) in black italics, and linear elements (links, faces) in gray italics. Symbols are as in Fig. 3. In all grid types, elements are ordered by y then x according to their geometric centers. Directional elements (links, faces) always point towards the top right quadrant. Rotational ordering is always counter-clockwise from the positive x-axis (right/east). This includes angle measurements. Examples of calls to grid properties are shown alongside each grid type to illustrate the expression of these ordering rules in practice. Note that corners, faces, and cells are not shown in (b) for clarity.

Figure 5: Interplay of node and link boundary conditions on a Landlab example grid. Because nodes rather than corners define the outer margin of the grid structure, the perimeter nodes lack cells, and the perimeter links lack faces (see main text). These aberrant nodes and links are automatically set as boundary elements. Landlab defaults to setting the condition of any such node to `FIXED_VALUE_BOUNDARY` and any such link to `INACTIVE`.

Figure 6: Interaction of timescales between a Landlab driver and a set of components. In this example, a driver that implements components 1–4 has a time loop of length *dt*, and *dt* is the timescale that is passed to the components. Components 1 and 2 implement numerical schemes that have maximum stable timesteps shorter than *dt*. In these cases, the

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imposed *dt* interval is internally subdivided to ensure the model remains stable. Here, we see two possible ways a component might do this, either always taking the largest timestep possible then a short timestep to finish (component 1), or by dividing the imposed timestep into the minimum number of equal length internal steps, dt_{int}, where $dt_{int} < dt_{stable}$ (component 2). Even if a component could run for a timestep longer than *dt* (e.g., components 3 and 4), under an explicit-time Landlab driver script like this, its steps will be truncated at *dt*. Once all the components have run for *dt*, they sequentially update their output fields in the grid with their changes. This is the only time that information can be passed actively between each component (and the driving script, if it also makes changes to the grid fields within the loop); each component cannot "feel" changes being made by any other until *dt* has elapsed. Hence *dt* is best thought of as the "coupling timescale".

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Figure 7: Schematic illustration showing how Landlab's grid geometry may be used to construct a finite-volume numerical scheme. White squares represent nodes, with example node IDs given for a 5x5 raster grid. Gray ovals show the centre points of the links, with the link IDs given. In this example, we assume that we have a node field called "elev" whose values represent the altitude of the land surface at various node locations (example values shown in italics next to each node). Black arrows indicate direction of soil flow (in the down-hill direction). A finite-volume solution for a diffusion model can be implemented by (1) calculating the gradient at each pair of adjacent nodes and assigning it to the corresponding link (lines 1–3 in the code snippet below), (2) multiplying by a transport-rate coefficient (and -1) to obtain unit flux (lines 4–6), and (3) multiplying the unit flux at each cell face by the width of that face, and adding up the inflows and outflows, and dividing by cell area to obtain flux divergence (lines 7 and 8).

Figure 8: A simple finite-volume hillslope diffusion model implemented in Landlab. Values adopted here are within typical terrestrial ranges for hillslope length (~100 m, controlled from line 3), hillslope diffusivity (0.01 $m^2 y^{-1}$, line 6) (Fernandes and Dietrich, 1997), total time of run (around a million years, since *dt* ~ 1833 y, lines 7-8), and uplift rate relative to base level (0.001 m y^{-1}, line 9).

Figure 9: Hillslope diffusion implemented in Landlab using a component. Compare to Fig. 8. Note that this version is more concise, and that timestep stability is now handled internally within the component.

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Figure 10: Performance of a Landlab-built model of landform evolution, using the StreamPowerEroder, FlowRouter, and PrecipitationDistribution components on grids of different types and sizes. Runs were performed on a Mid-2014 Macbook Pro, and each data point represents the mean of five runs. (a) Total time for a simulation of 3 million years, implementing a stochastic storm sequence of around 3000 distinct stormy intervals. Both the total time to run and the time spent in the loop in the code that iterates forward in time are shown, and are practically indistinguishable in most cases. The time to run the components is close to linear with number of nodes, as expected for the Fastscape algorithms (see main text). (b) The time spent initializing the grids and components in each case (i.e., the total time less the time spent in loop from (a)).

Setting up a Voronoi-based grid is more computationally expensive than a raster, but both are quick in absolute terms, and both are close to linearly scaled with the number of nodes. In both graphs, small deviations from linear scaling occur, probably related to the interaction of Python's dynamic memory management with the size of the random access memory on the individual machine.

Figure 11: Simulated topographies produced from a simple stream power-based fluvial incision rule, combining the StreamPowerEroder, FlowRouter, and PrecipitationDistribution components. The same model set up is implemented on both a RasterModelGrid (a) and a HexModelGrid (b), using the same random seed to generate the topography. Note the vertical-horizontal asymmetry in channel network planform visible in (b), an expected outcome of the three axes of mirror symmetry running though a hexagonal grid. The linearity of these catchment planforms is enhanced by the presence of an erosion threshold.

Figure 12: Simulated topographies produced from a coupled hillslope and channel evolution model, combining the StreamPowerEroder, FlowRouter, and LinearDiffuser components. A storm sequence is provided by the PrecipitationDistribution component, and discharge is routed across depressions in topography using DepressionFinderAndRouter. Stream-power parameters are identical to those in Fig. 11. The same model setup is implemented on both a RasterModelGrid (a) and a HexModelGrid (b), using the same random seed to generate the topography. Despite the differences in grid organization, planform drainage pattern remains fairly similar between the two cases.

Figure 13: Example of a CellLab-CTS model. Here the CellLab-CTS framework has been used to implement a model of granular mechanics. The model has eight node states, representing air (white), a resting grain (light grey), and a grain moving in each of the six lattice directions (all coded as dark grey). Grid edges and immobile walls are treated as `CLOSED_BOUNDARY` Landlab boundary conditions (black). Transition rules are used to model grain motion, grain collision, and gravity (from Tucker et al., 2016).

Figure 14: Implementation of an ecohydrology model in Landlab. (a) Schematic illustration of coupling among different Landlab components for the CaTGraSS application. (b) Demonstration of the model on a flat surface with semi-arid climate similar to that of Sevilleta, New Mexico, USA (Zhou et al., 2013). This figure plots percentage of space occupied by each PFT with time. (c) Spatial organization of PFTs at different times during the model run. These plots illustrate competition between different PFTs for space and resources. Trees die early within the first 300 years due to unfavorable climatic conditions and competition from shrubs and grass. The ecosystem swings between shrub-dominant and grass dominant states for the next 1600 years.

Figure 15: Demonstration of OverlandFlow component capabilities. The example shows development of a hydrograph in a catchment drawn from an airborne Lidar-derived DEM of the Spring Creek catchment in central Colorado, USA. The run uses a constant rainfall rate of 25 mm h^{-1} and a storm duration of 1 h. The hydrograph persists for almost 8 model hours, and water depth as plotted at several intervals after the start of the precipitation event: 1 h (the end of the storm), 2 h, 3 h, and 8 h.

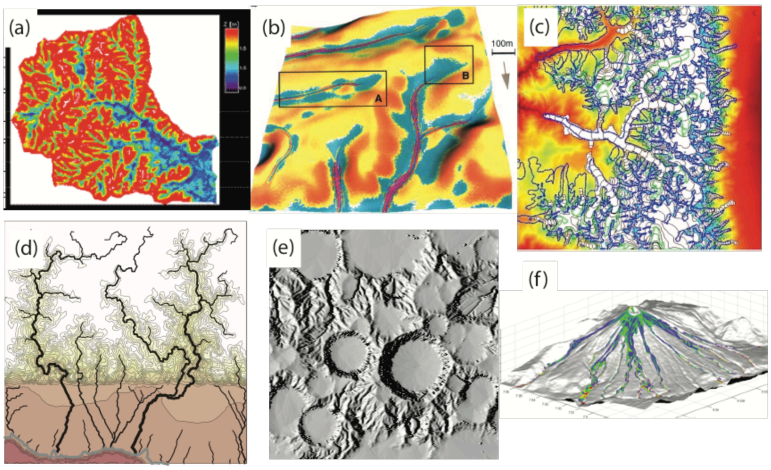


Figure 1

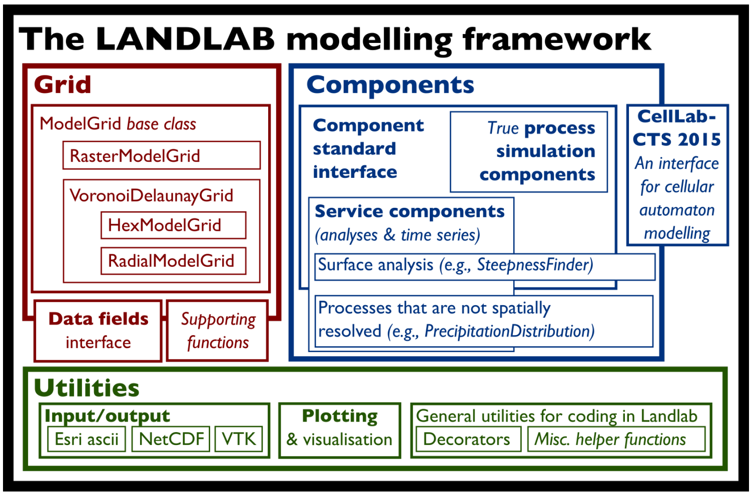

The LANDLAB modelling framework
Grid
ModelGrid base class
RasterModelGrid
VoronoiDelaunayGrid
HexModelGrid
RadialModelGrid
Data fields interface
Supporting functions
Components
Component standard interface
True process simulation components
Service components (analyses & time series)
Surface analysis (e.g., SteepnessFinder)
Processes that are not spatially resolved (e.g., PrecipitationDistribution)
CellLab-CTS 2015
An interface for cellular automaton modelling
Utilities
Input/output
Esri ascii
NetCDF
VTK
Plotting & visualisation
General utilities for coding in Landlab
Decorators
Misc. helper functions

Figure 2

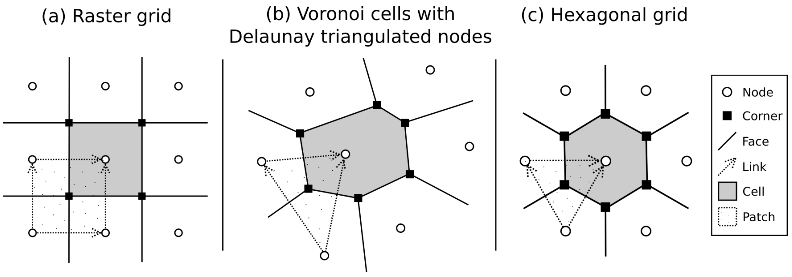
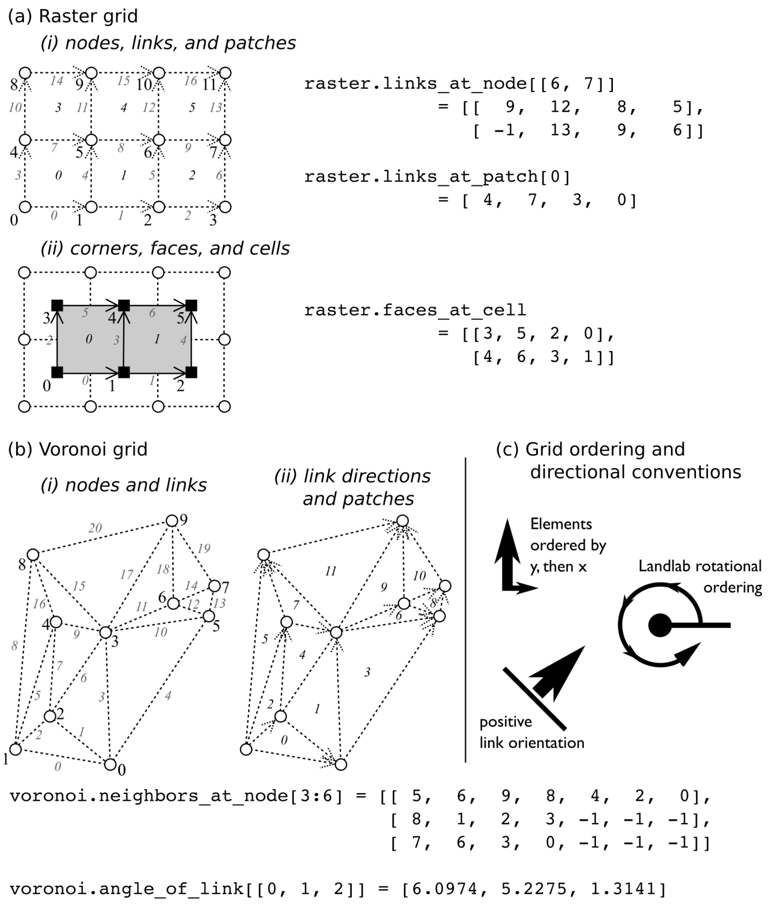

(a) Raster grid
(b) Voronoi cells with Delaunay triangulated nodes
(c) Hexagonal grid
Node
Corner
Face
Link
Cell
Patch

Figure 3



```
raster.links_at_node[[6, 7]]
                 = [[  9,  12,   8,   5],
                    [ -1,  13,   9,   6]]

raster.links_at_patch[0]
                 = [ 4,  7,  3,  0]
```

```
raster.faces_at_cell
                 = [[3, 5, 2, 0],
                    [4, 6, 3, 1]]
```

```
voronoi.neighbors_at_node[3:6] = [[ 5,  6,  9,  8,  4,  2,  0],
                                   [ 8,  1,  2,  3, -1, -1, -1],
                                   [ 7,  6,  3,  0, -1, -1, -1]]

voronoi.angle_of_link[[0, 1, 2]] = [6.0974, 5.2275, 1.3141]
```

Figure 4

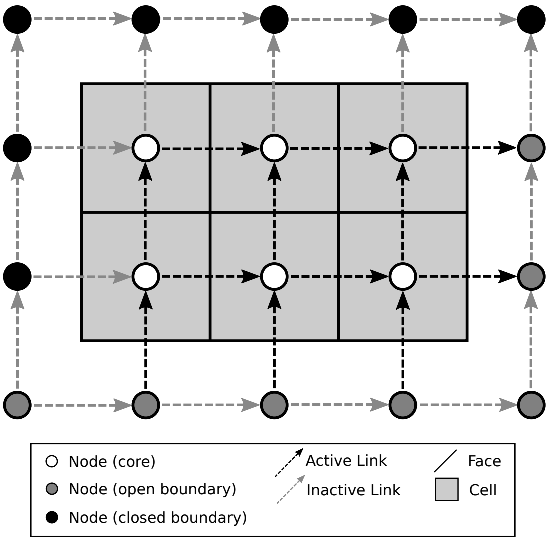

Node (core)
Node (open boundary)
Node (closed boundary)
Active Link
Inactive Link
Face
Cell

Figure 5

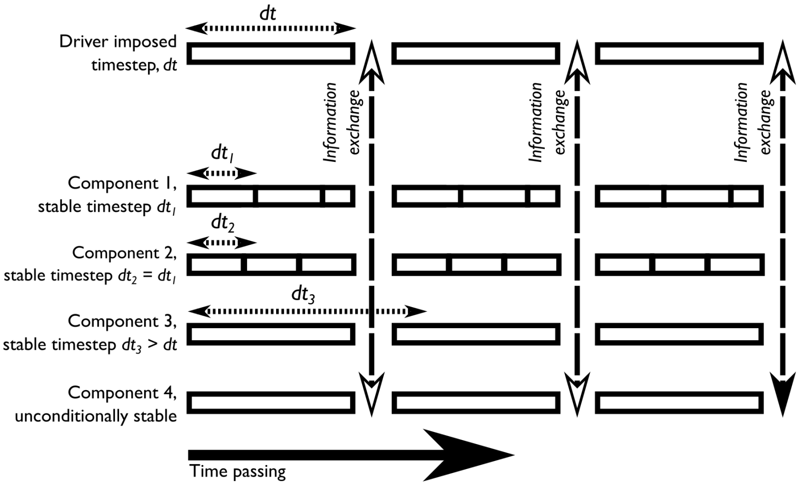
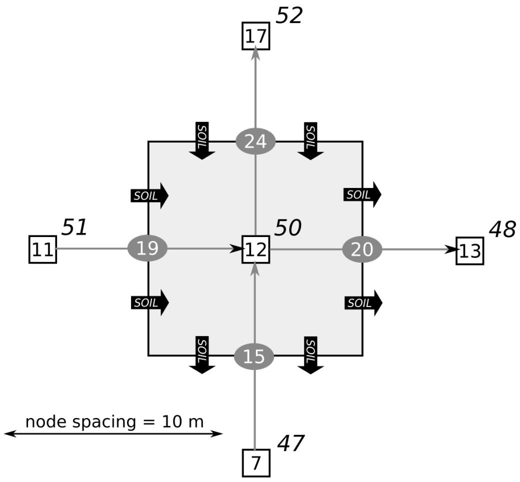

dt
Driver imposed timestep, dt
Information exchange
Information exchange
Information exchange
dt_1
Component 1, stable timestep dt_1
dt_2
Component 2, stable timestep $dt_2 = dt_1$
dt_3
Component 3, stable timestep $dt_3 > dt$
Component 4, unconditionally stable
Time passing

Figure 6



```
Calculating gradients at links:
>>> grad = grid.calc_grad_at_link(elev)
>>> grid.links_at_node[12]
array([20, 24, 19, 15])
>>> grad[grid.links_at_node[12]]
array([-0.2,  0.2, -0.1, 0.3])

Calculating fluxes from gradients:
>>> q = -0.01 * grad
>>> q[20]
0.002
>>> q[15]
-0.003

Calculating flux divergence:
>>> divq = grid.calc_flux_div_at_node(q)
>>> divq[12]
0.0002
```

Figure 7

Code to implement a simple diffusion model on a radial Landlab grid:

```
>>> from landlab import RadialModelGrid, imshow_grid
>>> from matplotlib.pyplot import show
>>> mg = RadialModelGrid(num_shells=10, dr=10.)
>>> z = mg.zeros('node')
>>> qs = mg.zeros('link')
>>> diffusivity = 1.e-2
>>> dt = 0.2 * mg.length_of_link.min() ** 2. / diffusivity
>>> for i in range(500):
...     z[mg.core_nodes] += 0.001*dt
...     g = mg.calc_grad_at_link(z)
...     qs[mg.active_links] = -diffusivity * g[mg.active_links]
...     dqsdx = mg.calc_flux_div_at_node(qs)
...     dzdt = -dqsdx
...     z[mg.core_nodes] += dzdt[mg.core_nodes] * dt
>>> imshow_grid(mg, z, grid_units=('m', 'm'), var_name='Elevation (m)')
>>> show()
```

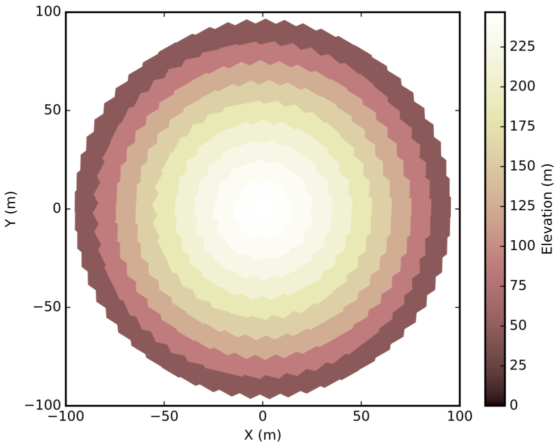


Figure 8

Code to implement a simple diffusion model on a radial Landlab grid, using Landlab components:

```
>>> from landlab import RadialModelGrid, imshow_grid
>>> from landlab.components import LinearDiffuser
>>> from matplotlib.pyplot import show
>>> mg = RadialModelGrid(num_shells=10, dr=10.)
>>> z = mg.add_zeros('node', 'topographic__elevation')
>>> dt = 2000.  # no longer the stable timestep
>>> ld = LinearDiffuser(mg, linear_diffusivity=1.e-2)
>>> for i in range(500):
...     z[mg.core_nodes] += 0.001*dt
...     ld.run_one_step(dt)
>>> imshow_grid(mg, z, grid_units=('m', 'm'), var_name='Elevation (m)')
>>> show()
```

Figure 9

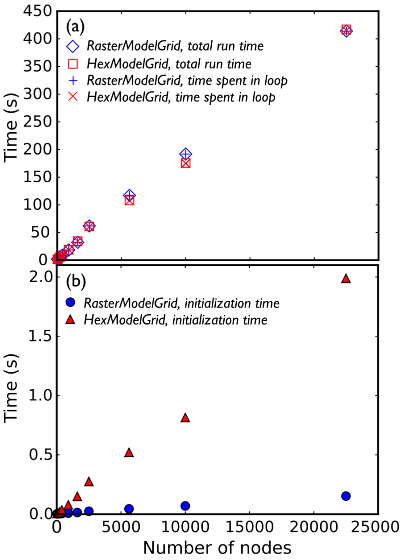

(a)
RasterModelGrid, total run time
HexModelGrid, total run time
RasterModelGrid, time spent in loop
HexModelGrid, time spent in loop
Time (s)
450
400
350
300
250
200
150
100
50
0
(b)
RasterModelGrid, initialization time
HexModelGrid, initialization time
Time (s)
2.0
1.5
1.0
0.5
0.0
0
5000
10000
15000
20000
25000
Number of nodes

Figure 10

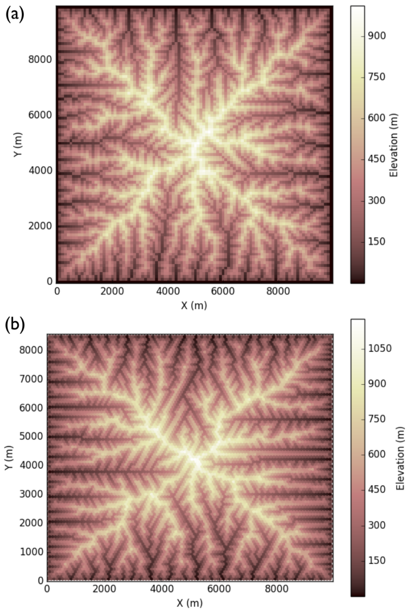

(a)
Y (m)
8000
6000
4000
2000
0
X (m)
0
2000
4000
6000
8000
Elevation (m)
900
750
600
450
300
150
(b)
Y (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
X (m)
0
2000
4000
6000
8000
Elevation (m)
1050
900
750
600
450
300
150

Figure 11

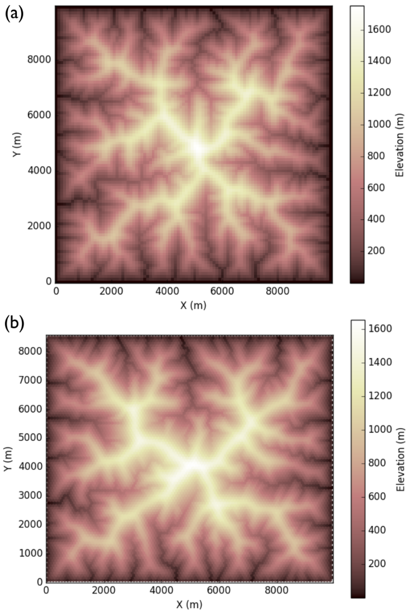

(a)
Y (m)
8000
6000
4000
2000
0
X (m)
0
2000
4000
6000
8000
Elevation (m)
1600
1400
1200
1000
800
600
400
200
(b)
Y (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
X (m)
0
2000
4000
6000
8000
Elevation (m)
1600
1400
1200
1000
800
600
400
200

Figure 12

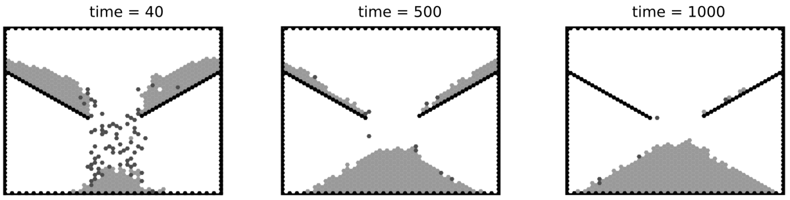


Figure 13

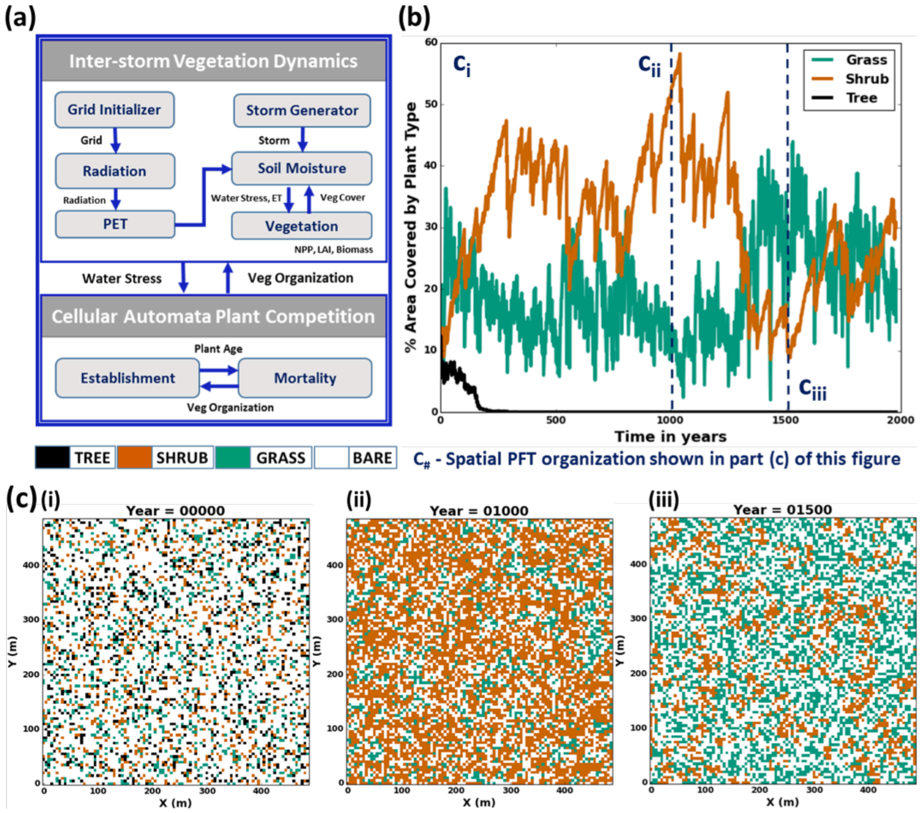

(a)
Inter-storm Vegetation Dynamics
Grid Initializer
Grid
Radiation
Radiation
PET
Storm Generator
Storm
Soil Moisture
Water Stress, ET
Veg Cover
Vegetation
NPP, LAI, Biomass
Water Stress
Veg Organization
Cellular Automata Plant Competition
Plant Age
Establishment
Mortality
Veg Organization
(b)
C_i
C_{ii}
C_{iii}
Grass
Shrub
Tree
% Area Covered by Plant Type
0
10
20
30
40
50
60
0
500
1000
1500
2000
Time in years
TREE
SHRUB
GRASS
BARE
$C_\#$ - Spatial PFT organization shown in part (c) of this figure
(c) (i)
Year = 00000
(ii)
Year = 01000
(iii)
Year = 01500
Y (m)
0
100
200
300
400
X (m)

Figure 14

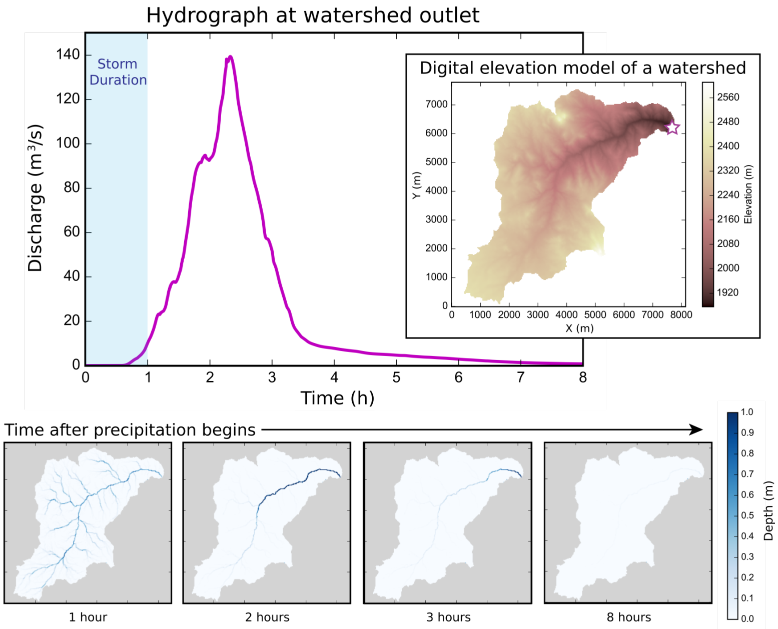

Hydrograph at watershed outlet
Storm Duration
Discharge (m³/s)
Time (h)
0
20
40
60
80
100
120
140
0
1
2
3
4
5
6
7
8
Digital elevation model of a watershed
Y (m)
X (m)
Elevation (m)
2560
2480
2400
2320
2240
2160
2080
2000
1920
Time after precipitation begins
1 hour
2 hours
3 hours
8 hours
Depth (m)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

Figure 15