Diffusion: Key to Horticulture Innovation Systems

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Abstract. *Horticulture, a pillar of the Dutch economy, has already achieved remarkable productivity increases through the use of natural gas for heating, lighting and CO2. Further innovative technologies that could aid the transition toward sustainable energy use, including heat/cold storage and deep-geothermal heat sources, are currently in development and spreading. However, there is a need to better understand the processes of technology diffusion in this industrial cluster to help stakeholders retain their competitive advantage and establish the best way to influence the energy future in the region and in the sector.*

This presentation discusses the experimental results of a series of agent based models of the greenhouse horticulture sector in the Netherlands, simulating the technological innovation decisions of greenhouse growers. Surveys of greenhouse growers suggest that innovation decisions are made on the basis of personal experience and information shared from other growers. In the model, each greenhouse grower must learn how to operate a greenhouse by evaluating their repertoire of technologies, exchanging information with other growers about their technological evaluations and purchasing new technologies to augment, expand or replace the existing selection. The interactions of greenhouse growers and the flow of information between them lead to emergent patterns, including diversity, adaption and complexity, in the diffusion of technologies throughout the community.

These emergent patterns of diffusion indicate that technological innovations develop and spread according to evolutionary mechanisms, suggesting that influencing, supporting or advocating the diffusion of sustainable technologies in this sector must also follow evolutionary mechanisms. As an evolving system, the reality of technology, innovation and transitions may require new approaches to management that work with, rather than against, the properties of evolving systems. Survey results, horticulture cluster background, model design and simulation results will be presented and implications for regional industrial management are discussed.

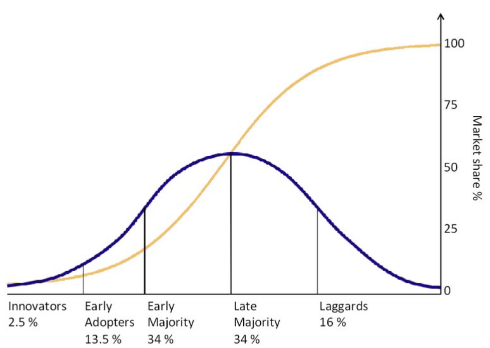
Keywords. *Innovation, diffusion, evolution, agent-based model, policy*

1 Introduction

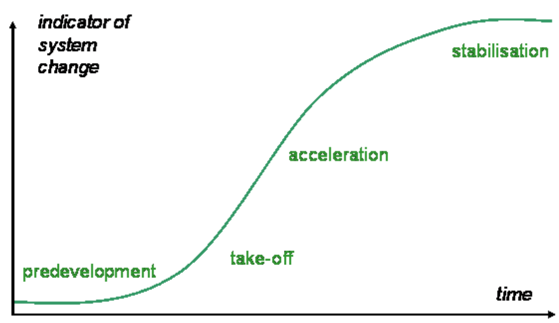
Horticulture, or the industry and science of plant cultivation, is growing in importance world-wide as food production comes under greater scrutiny. The Westland area, in the Netherlands, is well known for its long-standing, innovative, technologically advanced and economically valuable greenhouse horticultural industry (Hietbrink et al., 2008), providing a good case study for investigating the horticultural industry.

Discovery of an enormous Dutch gas field in 1959 (Verbong and Geels, 2007, Botter, 2009) motivated a national switch to natural gas as a primary fuel source, and government policy at the time lead to high resource use. In this boom time, energy conservation was a low priority, and growers optimized growing conditions with effective but fuel intensive heating, lighting, aeration, irrigation, transport, fertilizers and machinery (Heischel, 1976, Walsingham and Spedding, 1976, Tomczak, 2005). These popular innovations quickly diffused through the Westland greenhouses.

The theory of innovation diffusion was developed to account for observations of the way innovations spread through populations such as the greenhouse growers of the Westland. Later, the related theory of transition management has been used to describe observed diffusions and transitions in the past and also to inform policy decisions from governments, companies and communities as they seek to encourage the diffusion of particular innovations as part of a desired future transition (Stoneman and Diederen, 1994). The innovations can be almost anything, including new technologies, processes, or ideas and the populations can also vary widely, ranging from individual people to families, companies or governments. But no matter the innovation or population, successful diffusions are depicted as spreading through a population much like a virus, follows the same logistic function, or S-shaped curve (see Figure 1a). The process begins when a few individuals are exposed to an innovation and become persuaded that it has advantages or benefits. They then pass through stages of adoption, implementation and confirmation. The early adopters share their subjective perceptions of the innovation along available communication channels, acting as a source of information or persuasion for others, until finally even the laggards adopt and the rate of new adoptions plateaus or declines (Figure 1a). Many factors have been observed to influence the success or speed of diffusions, such as social systems and norms, the actions of opinion leaders and change agents, the nature of the innovation itself and the observed consequences of adoption. (Rogers, 1995).



(a)



(b)

Fig. 1. The S-shaped curve that emerges as an innovation diffuses, laid over the adopter categories, according to the theory of innovation diffusion *(a)* and the S-shaped curve as a system transitions from one stable state to another according to transition management theory *(b)*. Both curves are set with time along the X axis and some measure of change, market penetration, or adoption on the Y axis.

The Westland has a clear history of successfully diffusing cutting edge and highly visible greenhouse technologies. The gradual process of change in the structure of an important part of society is called a transition (Rotmans et al,, 2001), and although diffusions and transitions are working at different scales, transitions are usually understood to be the large scale sets of multiple diffusions, such as those in the Westland greenhouse sector. The theories of innovation diffusion and transmission management would both suggest that a key factor in the Westland's successful transitions and diffusions is the regular communicating between greenhouse growers, and between growers and government, business and academic experts. This communication provides the contact that allows information about innovations to spread, a prerequisite for diffusion.

Yet fossil fuels grow increasingly scarce and expensive, forcing growers to innovate in order to balance energy use and yield (Heischel, 1976, Walsingham and Spedding, 1976, Tomczak, 2005, Peters, 2008). Authorities are eager to diffuse innovations that can help (Verbong and Geels, 2007), but innovations that maintain high-yield growing conditions with less energy use, such as heat/cold storage and deep-geothermal heat sources, are not widespread (Ryback and Sanner, 2000) and are not diffusing well(TNO, 2010). Despite high levels of interest in using such heating sources for Dutch greenhouse horticulture (TNO, 2010), uptake in the Netherlands has not matched that of other countries (Lund and Freeston, 2001). Policies designed to encourage such diffusions can only say that the communicative networks that should drive the spread of the low energy innovations are already in place, suggesting that while the communication is necessary for effective diffusion, it is not sufficient. Meanwhile, other research suggests that industries and technologies are complex adaptive systems and develop according to complex and diverse mechanisms for evolution rather than just diffusion (Kasmire et al., 2011, Chandler, 2005, Kelly, 2010, Fleming and Sorenson, 2001).

Diffusion theory is a simple, non-evolutionary theory, originally used to describe the past. Transition management claims to be an evolutionary theory, a conjecture that the authors dispute but which falls outside the scope of this paper, but the clear similarities to diffusion theory suggest that it may not account well enough for the complex and evolving nature of a system's future. Governments and businesses are basing development plans on transition management (Shove and Walker, 2007) and diffusion theory, which may be inadequate. The solution may lie in combining the descriptive power of diffusion theory with the exploratory power of Agent Based Modelling (ABM) to produce an evolutionary theory of innovation diffusion.

2 Evidence of diffusion in the Westland

The Westland underwent a major transition from the traditional Westland Greenhouse to the modern Venlo Greenhouse in a matter of decades (Berker and Geels, 2011), involving the diffusion many innovations, including artificial heat and light, watering systems, new crop types, disease control techniques and the use of CO2 enrichment. This transition, or rapid diffusion of so many innovations, lead to numerous studies concluding that flows of information, expertise and knowledge along networks of growers were crucial for success. (Pannekoek et al., 2005, Buurma and Ruijs, 2011). These findings match the intuitions of the greenhouse growers themselves, as reported in a small scale survey about technology investment decisions (van den Berg, 2010, Kasmire et al., 2011). Most greenhouse growers hold strong opinions about the performance of technologies in their own greenhouses and definitively stated that they value their own experience first and foremost. Growers were also keenly interested in the technologies and performance of their neighbors, and value the input from other growers when deciding on new investments. Far less valuable to the growers was information provided by governments, technology companies or academic studies. For this reason, communities, associations and other greenhouse grower networks are very popular and provide the most important source of information for growers looking to make technology purchases.

Evidence of past successful diffusions in the Westland, and the intuitions of the growers, match the theory of innovation diffusion, but they also match the expectations of evolutionary mechanisms governing complex adaptive systems (Kasmire et al., 2011, Dooley, 1997). Universal Darwinism (UD) argues that many non-biological things evolve under the same basic mechanisms as species, and consequently display the same emergent behaviours, including diversification, speciation, convergence, stasis, evolutionary drift, satisficing fitness, developmental lock, vestiges, niche competition, punctuated equilibria, emergence, extinction, co-evolutionary stable strategies, arms races, ecological interdependence, increasing complexity, self organization, unpredictability, path dependency, irreversibility and progress (David, 2000).

By embracing the evolutionary nature of complex adaptive systems, UD based theories would suggest that the S-shaped curves found in innovation diffusion and transition management theories are only visible from a limited perspective, are only one of many possible patterns, and are not an appropriate policy goal. Moving a complex adaptive system from one pattern to another is no simple matter, and to attempt to do so demands a better foundation than observations of a limited number of non-replicable past diffusions.

3 Models of diffusion

Models of diffusions typically resemble the top-down, pattern focused models used in epidemiology theory, where the innovation is viewed as equivalent to an infection (Goldenberg et al, 2000, Weisbuch and Stauffer, 2000, Abrahamson and Rosenkopf, 1997), with information replacing germs and social contact in place of physical contact. The objects of study are top level, emergent behaviours, such as the total level of infection or adoption, the rate of infections or adoptions, or the critical point after which further infection or adoption is inevitable. Lower level interactions, such as when contact is established between individuals and what happens, lead to these higher level patterns, but are simplified or ignored. The top-down bias even pervades any attempt to include the individual, as when studies examining early adopters found that they share certain characteristics. These characteristics, such as education level, income or status (Rogers, 1995) were correlated to early adopters without questioning the fact that "early adopter" is a globally assigned, top-down classification, based on calculations that cannot be determined until the diffusion is complete (Figure 1a). Even when the characteristics of individuals, populations or innovations are explicitly studied or modeled, the results are reported only in relation to their effect on the higher level patterns (Sebastiano et al., 2007), with no interest for how they effect the interactions that lead to those patterns.

In addition to being fundamentally top-down, these models require simplifications that, while useful for examining past diffusions, are useless for modeling future diffusions. One such simplification is the focus on successful diffusions. Certain innovations do appear to diffuse in an S-shaped curve when viewed from the right perspective, but others do not, even with the same communicative networks, as is happening with heat/cold storage systems now. A second simplification is the way successful innovations are defined as whatever collection of features has diffused successfully, even if the innovation and its features changed significantly during the diffusion. For example, combined heat and power systems have diffused quite well, (Verbong and Geels, 2007) can only be said to have diffused in an S-shaped curve if we equate early and later examples, and one competitor's model with another, despite the many dissimilarities between them. Another simplification is viewing the innovation as moving and the population as static when human populations are definitely dynamic. The time frames at which viruses spread mean that population size is important, but population turnover (births and deaths, essentially) is less so. But the decades long diffusion for greenhouse innovations means that turnover is quite important, as are changes in the communicative networks, population growth, and many other ways the population could change. Further simplifications include treating sufficient exposure to an idea as leading to adoption (exactly as if it were contagious), ignoring the dynamics of competing innovations (by studying the diffusion one innovation without the context of predecessors, competitors or replacements), and ignoring the fact that diffusions are desirable while infections are best avoided. The failure to notice that a fundamental difference in system drivers, such as avoiding or encouraging, as well as the many other simplifications, come from the top-down focus, backward looking approach of a fundamentally non-evolutionary model that seeks to reduce complexity in order to explain past observations.

Diffusion theory and the related transition management theory, appear to lack the power to deal with in-progress or proposed diffusions where the data is not yet available, the final states are unknown and complexity cannot be reduced, but a properly evolutionary theory can do much better, but the same information can be seen though a different lens. A UD theory would examine why some innovations succeed while others do not, how and innovations change during diffusion, how the diffusion and changes of an innovation relate to population dynamics, and what might happen next.

4 ABM of diffusion

Agent Based Models (ABM) are good for exploring complex situations when there is little insight as to what exactly will happen in the big picture (Borshchev 2004) because by they examine multiple possible outcomes. ABMs consist of a number of autonomous agents, embedded in an environment, who act and interact in parallel. By allowing the agents to react independently, according to their own environment, experience and rules, ABM is distinctly bottom-up, with no central control and with a wide variety of possible emergent states. ABMs are also excellent at modeling complex structures, like the communicative networks that diffusion theory finds so vital, while permitting dynamic elements that diffusion theory cannot now incorporate (Borshchev 2004). ABMs can handle the added complexity of dynamic individuals, populations, structures, interactions and innovations, allowing these elements to change as they do in the real-world.

This paper presents the results of two experimental ABM simulations of the greenhouse horticultural sector in the Westland that advances diffusion theory by adding evolutionary mechanisms. The models use important elements of diffusion theory, such as the communication channels and the distinct stages of innovation adoption, but are explicitly bottom-up, with dynamic agents and a dynamic population. Other aspects could have been dynamic, such as the structure of the communicative networks or the efficiency of the technology innovations, but these will be investigated in future instantiations of the model. Instead, this model establishes the value of diffusion theory when some of the non-evolutionary, top-down, backward looking assumptions are removed.

4 Model description

The agents represent greenhouse growers or greenhouse companies who must sell produce and use the profits to invest in new technologies. All agents form opinions of the technologies that they own, and then share these opinions with their neighbors (see Figure 2 for a schematic model layout). When they purchase a technology, they choose the one for which they have the highest opinion and which they can afford, with a small

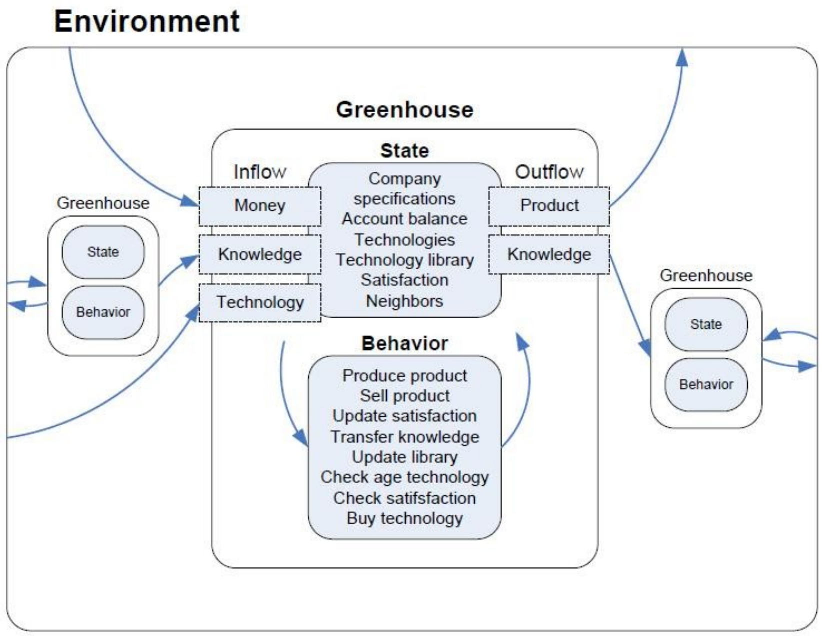


Fig. 2. A schematic layout of the greenhouse grower agent based model

chance of purchasing a technology for which they have no opinion. Model 1 starts with all agents receiving a random selection of all available technologies, with the expectation that growers who happen to have better performing technologies will spread positive opinions of them and stimulate a diffusion. Model 2 starts with all agents having no technologies whatsoever, but the small chance of purchasing an unknown technology provides the possibility for technologies to diffuse. This section details the model setup and operation for both models.

4.1 Agent and technology description

Agents are assigned a greenhouse size ranging from 1 to 25 hectares, according to a power law distribution, roughly approximating the distribution of greenhouse sizes in the Westland. Each agent is connected to a number of neighbors, also following a power law distribution, to mimic the social networks observed among greenhouse growers. Agents are given a credit balance and an empty opinion library to record their satisfaction with the various technologies encountered during the simulation. The agents also receive a stubborness quotient, describing how an opinion based on their own experience is weighted with respect to the opinions of others, an innovativeness quotient, describing how likely the agent is to disregard their opinion tables and try a technology for which they have no information, and an opinion change rate, describing how new information is weighted against old when forming opinions. Agents are also assigned a random crop type, either flowers or vegetables, which entail different production functions, including base costs, operating costs and production values to represent the differences between flower and vegetable production. The crop type cannot be changed, but agents that go bankrupt will be re-initialized and may receive a new crop type.

Each technology belongs to one of three categories, meant to represent heating, lighting and irrigation systems, and agents are limited to one technology from each category at any one time in the simulation. Each technology has a purchase price, an operating cost, a maximum lifespan, a current age, and a performance value representing the effect on production. One technology from each category represents the optimum for each crop, with all non-optimal technologies costing more to operate or producing fewer crops. In model 1, agents begin with one randomly assigned technology in each technology category, while in model 2, all agents are initialized with a "non-technology", which has no cost or effect on performance, in all three categories.

4.2 Modeling assumptions

Although the model represents a real, geograghic area, physical distance is not expressly modeled, as the transfer of information is expected to be unaffected by physical distance within the regional cluster. The crop types are initially distributed randomly, as are the technologies in model 1. Technologies are not explicitly fed into the model in order to see the diffusion, rather the agents with relatively good technologies act as a source of the diffusion process. When an agent is unprofitable and runs out of credit, it will be reinitialized with new company specifications, blank opinion libraries and a random selection of technologies (in model 1) or non-technologies (in model 2), but the greenhouse size and connections to neighbors do not change. This modeling simplification is meant to mimic the fact that in the densely packed Westland, greenhouses cannot readily change size, and that the number of growers associations available to new growers is also quite limited. The different actions of the agents all happen once per time step, meant to represent one year.

4.3 Time step and model operation

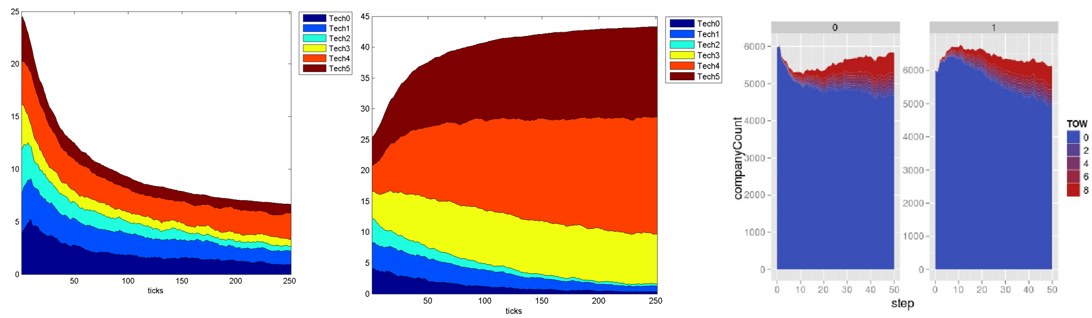
At each time step, the agents produce and sell their crops and subtract the current costs of greenhouse operation to find their profit. They then compare their profit to that of their neighbors, and update their opinion library by increasing their opinion rating for their current technologies if their profits compared favorably to their neighbors, and decreasing their opinions if they are less profitable. Agents then examine the technologies and the opinion tables of their neighbors and incorporate those opinions. If a current technology has reached its maximum age, the agent will examine the technologies in the same category and purchase the technology for which they have the highest opinion that they can afford. Non-technologies are also available for "purchase" in model 2, allowing agents to own no technology in a given category if their opinion tables justify it.

5 Model results and discussion

One important result is that in dynamic, non-heterogenous populations, it is very difficult to calculate S-shaped curves. In both of these models, differences between the production functions of the two crop types, combined with the different costs of the optimal technologies for each crop type and the possibility to be reinitialized with a different crop type after bankruptcy meant that although the total number of agents remained constant, the number of growers in each crop type did not. Although it was possible to track the total number of growers or the percentage of growers that adopted a paticular technology per crop type, no S-shaped curves were forthcoming (Figure 3).

Another important result is that even the best technologies do not always diffuse well. Because one technology is best for flower growers and another for vegetable growers, there is no universal optimal. In model 1, flower producers were less profitable than their vegetable producing neighbors, and were less satisfied with their technologies, even with the best flower technologies. They copied the technologies of the more profitable vegetable growers, went bankrupt more often and declined in numbers, which made them even more susceptible to copying the numerous vegetable growers. Thus, the best flower technologies, (Tech 0 followed by Tech 1) did not diffuse well among either flower or vegetable growers, while the best vegetable technologies (Tech 4, followed by Tech 5) diffused well among all growers (Figure 3, a and b). In model 2, all technologies diffused well among all growers (Figure 3c). In this model, differences in performance between crop types was non-existant at the beginning, and although flower growers suffered early losses in numbers, they eventually came back strong and outnumbered the vegetable growers. There was no clear influence for either crop as neither crop type was more profitable or more numerous overall. Although some technologies diffused well in both models, the population characteristics and dynamics rendered the usual assumptions and measurements meaningless. The S-shaped curve cannot deal with multiple optimal technologies, and has no way to capture competition, disruptive advice, and diverse agents.

Second, the vegetable growers in model 1 concentrated, but never completely converged, on the best technologies. Diffusion theory expects total or near total convergence as the adoption rate plateaus at the top of the S-shaped curve, but, as it does not account for actions beyond the original adoption, the theory has little to say about when or why the plateau occurs as it does. However, a UD theory recognizes that the information sharing mechanism, population, and competition levels are dynamic, so greenhouse growers can never afford to settle and must continually explore new options. Newly introduced greenhouse growers who have little experience also explore all options, but this behaviour is only found in dynamic models. The less common and less profitable flower growers, under pressure to compete with the vegetable growers and with conflicting experience and information, were even less likely to converge. In reality and in the simulations, greenhouses must experiment, diversify and adapt to deal with constant change and competition. Model 2 did not approach convergence, not even on the best technologies, so never saw a plateau. This would certainly indicate that the S-curve is a totally unrealistic ideal when a diffusion is too slow for the dynamics of the population, information sharing mechanisms and the introduction and development of innovations.



(a) *(b)* *(c)*

Fig. 3. Instead, Experiment 1 shows that, although better technologies, like Tech 4 diffused well and dominated the technology distribution, it did so for both vegetable growers *(a)* and flower growers *(b)*, who should have seen more diffusion of Tech 0. The change in population makes finding an S-shaped curve by crop type difficult, either for total or relative percentage of adopters. The change in population in model 2 *(c)* was not as clear cut as in model 1, and all technologies diffused to some extent.

To sum up, the simulations reveal several results that are best interpreted from an evolutionary view. Technologies may spread well, but only appear to do so in S-shaped curves when they are the best technologies for the most numerous or powerful group, and only when the populations are held constant. Some optimal technologies failed to diffuse well, while others diffused too well, having spread to growers who would do better with a different option. Further, the diffusions will never reach full convergence in dynamic, competitive populations, and may not even approach convergence if the populations, the innovation, or the communication system interact in unforeseen ways.

5 Future work and final conclusions

This paper presents one of many ways to combine diffusion theory with ABM to better explore complex adaptive systems such as greenhouse sectors. Further complexity could be added by varying or developing the technologies over time, perhaps growing more effective, economical, or efficient. In these models, the population only changed at the individual level, the level of each agent's learning, communication and behavior, and through the re-initialization of bankrupt agents. These individual changes contributed to the dynamics of the entire population, but more complex and realistic behaviour could be explored by allowing agents to build or break social connections, agents to group themselves by crop type or around the more successful agents. Finally, generational turnover can change the end results of shared, structured systems (Vogt 2006), because of the unique effects of introducing naïve agents, such as the newly initialized agents after a bankruptcy. Therefore, it might be very interesting to see a more realistic generational turnover in the model, featuring agent life spans, startup growers, and family businesses.

Diffusion theory is great for examining and explaining past diffusions, but cannot describe all aspects of introduction, diffusion and evolution of innovations, and can certainly not describe, predict or manage future diffusions. Despite its fundamental unsuitability to the task, diffusion theory forms the basis of many policies, plans and efforts from governments, regulators, business, and even individual people, and may result in ineffective policies, wasted money, unfair markets, failure to meet objectives. These policies may even be working against their own interest by using an inappropriate theoretical foundation. A better foundation must account for the evolutionary, competitive, dynamic nature of industries and technologies. As a possible improvement, UD captures not only what diffusion theory captures, but a lot more, and does so in a way that can be useful for on-going and future diffusions. UD does not seek to force an S-shaped curve, which is only one idealized emergent pattern, but to explore many possible patterns to see what interactions underlie them, all the better to deal with the real cause.

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