Adding a change resistance layer to integrated system models using root cause analysis and problem decomposition

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Abstract

Inspired by the iconic World2 and World3 system dynamics models, why has a long series of increasingly sophisticated integrated system models (ISMs), such as Threshold21, DICE, and iSDG, largely failed to lead to successful solution of the environmental sustainability problem? The paper proposes the main reason is these models suffer from a boundary problem, by excluding the critical component of political system change resistance. To begin the conversation for filling this gap, the paper presents a submodel to demonstrate how a change resistance layer can be added to an ISM, using World3 as an example. Scenario policy changes now go through the layer, which provides the necessary resistance. The use of root cause analysis and problem decomposition to create an effective layer is described.

The need for continual innovation

Early in his piece on *System dynamics at sixty: the path forward*, Sterman (2018) stated the core of his appraisal of Forrester's contribution to the field: (italics added)

> The main lesson of Jay's several careers does not lie in the particular tools or methods he developed, but in *the need for continual innovation* to solve important and difficult problems. Close examination of Jay's life reveals a relentless effort to make a difference on real and pressing problems. To do so, in each of his careers, Jay studied the then-new advances in *tools and methods* developed *in any discipline* relevant to the problem he sought to address, mastering the state of the art—and then built on those advances. The failure to appreciate Jay's real contribution *is a significant problem today* in the field of system dynamics.

If Forrester was alive and starting a new career today, what innovative tools and methods might he discern were necessary to solve extraordinarily difficult global problems like environmental sustainability? Given his deep business management background, perhaps he would borrow from that discipline, as we have done, and seize upon the powerful tools of *root cause analysis* and *problem decomposition*.

This paper argues that when confronted with truly difficult large-scale social problems, policy analysis using traditionally built ISMs is insufficient. If it were, then the increasingly more sophisticated models that began fifty years ago with World2 (Forrester, 1971) and continued with models like World3 (Meadows et al., 1972), the Triple Value Model (Fiksel, 2012), Threshold21 (Barney, 2002), DICE (Nordhaus, 2018), and iSDG and IFs (Pedercini et al., 2020), as well as global models focused on climate change, like C-Roads (Sterman et al., 2012), would have led to policies that mostly solved the environmental sustainability problem by now. However, they have not.

ISMs have excelled in problem definition and input to goal setting, such as the Sustainable Development Goals and the Paris Agreement. There have even been some gains, like local pollution and solution of the stratospheric ozone depletion problem. However, "decades of scientific monitoring indicate that the world is no closer to environmental sustainability and in many respects the situation is getting worse" (Howes et al., 2017). Such lack of progress indicates something in the policy analysis portion of these models needs considerable improvement. Something deeply fundamental is missing.

Business managers have long faced the same problem. Continually confronted with one novel difficult problem after another for centuries, business men and women invented thousands of new problem-solving tools and methods, and then refined them as necessary. While science gave the world the supremely powerful problem-solving tool of the scientific method (which solved the problem of how to create reliable new knowledge), business gave the world equally powerful problem-solving innovations like double entry accounting (how to correctly manage financial planning), mass production (how to scale production to large volume), and root cause analysis (how to solve any causal problem).

Given that the sustainability problem is a causal problem, and that no ISM we are aware of employs explicit root cause analysis, we propose that *the* missing two tools for construction of ISMs are root cause analysis and one of its key tools, problem decomposition. Without knowledge of a difficult problem's root causes, problem solvers tend to fall into the *Superficial Solutions Trap*. This occurs when people assume intermediate causes are root causes. It's a common trap, as Forrester (1971, p. 95) describes: (italics added)

> *The intuitively obvious 'solutions'* to social problems are apt to fall into one of several traps set by the character of complex systems. ...people are often led to intervene at points in a system where *little leverage exists* and where effort and money have but slight effect.
>
> ...social systems are inherently insensitive to most policy changes that people select in an effort to alter behavior. In fact, *a social system draws attention to the very points at which an attempt to intervene will fail*. Human experience, which has been developed from contact with simple systems, leads us to look close to the symptoms of trouble for a cause. But when we look, we are misled because the social system presents us with an *apparent cause* that is plausible according to the lessons we have learned from simple systems, although this apparent cause is usually a coincident occurrence that, like the trouble symptom itself, is being produced *by the feedback loop dynamics of a larger system.*

Forrester's "apparent cause" is what root cause analysis calls the intermediate cause. "Little leverage exists" if problem solvers assume the apparent cause is the root cause, because that leads to pushing on low leverage points.

This, we hypothesize, is what has occurred with ISMs. Despite integration of natural and human components, these models have "drawn attention to the very points at which an attempt to intervene will fail." Policies based on ISMs have unfortunately largely failed, indicating modelers have unknowingly fallen into the Superficial Solutions Trap. These policies attempt, in vain, to resolve "apparent causes" instead of root causes, as did the four conventional urban management policies that Forrester (1969) analyzed with his urban dynamics model. Contrary to expectations, none made the problem better. Some, particularly the most popular solution of the four, low-cost housing, made the problem substantially worse, a profoundly counterintuitive discovery.

However, by including factors and feedbacks that had not been considered before, Forrester showed that high leverage point policies that had long been overlooked existed. Pushing on the system's high leverage points (such as with "demolition of slum housing and replacement with new business enterprise", p71) resolved the problem's root cause(s), which were "being produced by the feedback loop dynamics of a larger system."

The analogy just described, of the urban decay problem and model versus the environmental sustainability problem and ISMs, carries an enticing morsel of good news. If ISM builders can innovate as Forrester did and enlarge their model boundaries to include factors containing the problem's main root causes, then the sustainability problem appears solvable.

The remainder of this paper addresses this opportunity. We begin with taming the extreme complexity of the sustainability problem by assembling the necessary tools into a suitable problem-solving process. This is followed by using the process to construct a model that includes the missing change resistance layer and the root causes of that resistance. We end with discussion and conclusions.

Taming problem complexity with the necessary tools

Necessary Tool – System dynamics

System dynamics was invented for the purpose of solving problems arising from complex feedback loop dynamics. However, successful application requires many tools, methods, and best practices (Forrester, 1961; Martinez-Moyano and Richardson, 2013; Sterman, 2000; Warren, 2008). How does one determine which must be applied to the environmental sustainability problem?

Necessary Tool – Integrated system models (ISMs)

That question was partially answered by creation of World3 (Meadows et al., 1974, 1972), the first detailed, fully calibrated, well-documented ISM to combine the natural and human systems into a single integrated model. By 2007 seven ISMs had appeared (Costanza et al., 2007). In 2018 the number of currently maintained global ISMs had grown to approximately eleven (Calvin and Bond-Lamberty, 2018). The chief feedback linkage between the earth and human systems has become emissions/temperature, as problem focus shifted from the broad range of World3 to the climate change crisis.

ISMs are seen as *the* tool for analyzing and solving the environmental sustainability problem, and highly influence global policy (Pedercini et al., 2020; van Vuuren et al., 2012). But as the intractable behavior of the problem has repeatedly demonstrated, ISMs have been ineffective. *We argue this has occurred mainly because of the lack of the right driver for asking the right questions on how to build an integrated model's most important components.*

Integrating the Tools – A problem-solving process that fits the problem

The right driver, we suggest, is *root cause analysis*. This tool centers on the method of the *Five Whys*, where starting at problem symptoms one asks "WHY does this occur?" until the root causes are found (Imai, 1986, p. 50; Ohno, 1988, p. 77). Such questions, in the hands of a well-trained experienced root cause analyst(s), will most of the time generate the right questions needed to build the right mental/physical models required to solve the problem, no matter how difficult the problem may be. This allows problem solvers to implement one of the maxims of industry: "The right process will produce the right results" (Liker, 2004, pp. 85–168).

However, industrial experience with root cause analysis has shown that in highly complex systems, root cause analysis itself requires its own driver, in the form of something that organizes the problem such that the fog of complexity is decreased to the point where WHY questions can be correctly asked and answered. The chief tool for this is *problem decomposition*, where the one big original problem is carefully decomposed into smaller and hence *much* easier to analyze subproblems.

This leads to the process shown in Figure 1. Each step is iterative and requires its own related tools, methods, and best practices. None of the five steps are new. Only their arrangement into a suitable process is new, and represents what Jay Forrester strived for throughout his life: "*the need for continual innovation* to solve important and difficult problems."

The first step, original problem definition, aka problem articulation (Sterman, 2000, p. 86) or problem identification and definition (Martinez-Moyano and Richardson, 2013), is well-described elsewhere.

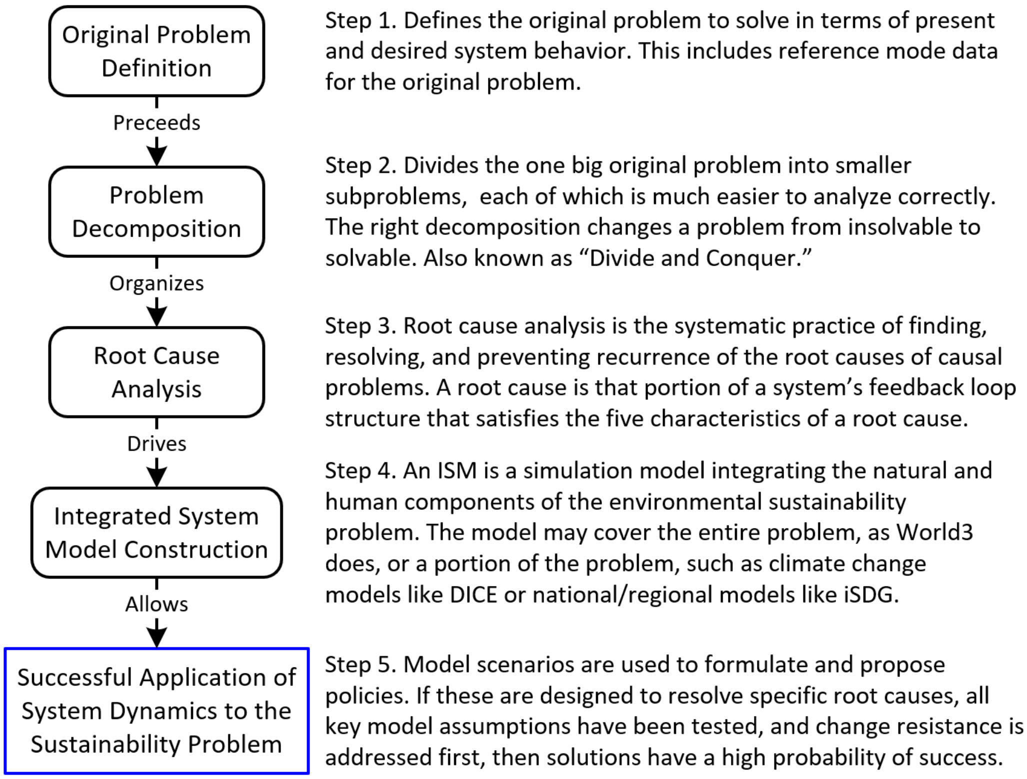

Figure 1. The RCA-based ISM process, showing the five high-level steps for taming extreme problem complexity. The diagram summarizes the thesis of this paper. Current practice for constructing ISMs lacks steps 2 and 3.

Necessary Tool – Root cause analysis (RCA)

RCA originated with the "King of Japanese Inventors," Sakichi Toyoda, in the early twentieth century when he formalized how he applied the method with the now ubiquitous *Five Whys*. Imai (1986, p. 50) describes the method:

> In the factory, problem solvers are told to ask "why" not once but five times. Often the first answer to the problem is not the root cause. Asking why several times will dig out several causes, one of which is usually the root causes. [For example:]
>
> 1. Why did the machine stop?
>   Because the fuse blew due to an overload. [intermediate cause]
> 2. Why was there an overload?
>   Because the bearing lubrication was inadequate. [intermediate cause]
> 3. Why was the lubrication inadequate?
>   Because the lubrication pump was not functioning right. [intermediate cause]
> 4. Why wasn't the lubrication pump working right?
>   Because the pump axle was worn out. [intermediate cause]
> 5. Why was it worn out?
>   Because sludge got in. [root cause]
>
> By repeating "why" five times, it was possible to identify the real cause and hence the real solution: attaching a strainer to the lubricating pump. If the workers had not gone

through such repetitive questions, they might have settled with [an intermediate cause solution], such as replacing the fuse.

Today, RCA serves as the foundational paradigm of widely used, highly refined business processes with high process maturity like the ISO 9000 family of international quality standards (Tummala and Tang, 1996), lean production (Womack et al., 1990), and Six Sigma (Pande et al., 2000). The leader is Six Sigma, used by 100% of aerospace, motor vehicle, electronics, and pharmaceutical companies in the Fortune 500 and 82% of all companies in the Fortune 100 (Marx, 2007).

Industrial RCA revolves around the concepts of defects and root causes. RCA is used to maximize the quality of solutions to customer's problems. Anything that displeases the customer is a defect. Defects arise from root causes. Six Sigma, an RCA-based process for radical improvement of core business processes, routinely cuts defect rates by an astonishing three orders of magnitude, from roughly 6,210 defects per million transactions to 3.4, as process maturity rises from a typical initial level of Sigma 4 to a final level of 6 (Pyzdek, 2003, pp. 5 & 60). RCA has become so central to quality management and problem solving that "Root cause analysis is an essential process for any organization that wants to continue to improve and is willing to engage in serious introspection and analysis" (Dew, 2003).

The RCA paradigm rests on several core concepts. Drawing from a diversity of sources, e. g. (Andersen and Fagerhaug, 2006; George et al., 2005; Ishikawa, 1986; Okes, 2019; Pyzdek, 2003; Tague, 2005), a root cause is the deepest cause in a causal chain (or the most basic cause in a feedback loop structure for more complex problems) that can be resolved. A causal problem occurs when problem symptoms have causes, such as illness or a car that won't start. Examples of non-causal problems are math problems, scientific discovery problems, information search/organization problems like criminal investigation, and puzzle solving. *All causal problems arise from their root causes.* The sustainability problem is a causal problem. It can therefore only be solved by resolving its root causes, whether root cause terminology is used or not. RCA employs hundreds of supporting tools and techniques. RCA is generic and for difficult problem use must be wrapped in a process tailored to the problem class.

From the vantage point of quality management, where all problems are seen as forms of unacceptable quality of solution of a customer's problem (note that citizens are customers of their governments), the business/engineering world has concluded that RCA is the only known core method for solving difficult causal problems reliably and efficiently, e. g. (Tague, 2005 pp 338-47, The Quality Improvement Process), just as the scientific method is the only known core method for creating reliable new cause-and effect knowledge. Other core methods, such as experimental trial and error, forms of statistical analysis like comparative and factor analysis, and simulation modeling, can sometimes eventually solve difficult causal problems. But they cannot do so reliably and efficiently because unless RCA is combined with these methods, the full causal structure of the problem remains hidden and the solution landscape cannot be navigated efficiently.

Root cause analysis is the systematic practice of finding, resolving, and preventing recurrence of the root causes of causal problems. For the class of difficult large-scale social problems like sustainability, a strong definition of root cause is required: A *root cause* is that portion of a system's feedback loop structure that, using the checklist below, explains why the system's structure produces a problem's symptoms. The checklist allows numerous unproductive root causes (particularly intermediate causes posing as root causes) to be eliminated. The five requirements of a root cause are:

1. It is clearly a (or the) major cause of the symptoms.
2. It has no worthwhile deeper cause. This halts the asking of "Why did this occur? What is its cause?" at an appropriate point.
3. It can be resolved, by pushing on its high leverage point(s) to initiate the desired mode change in complex problems, or to merely change the node with the root cause in simple problems. (Mode change versus node change)
4. Its resolution will not create other equal or bigger problems. Side effects must be considered.
5. There is no better root cause. All alternatives have been considered to the point of diminishing returns.

The first three requirements are from (Harich, 2010). In the spirit of continuous process improvement, two more have since been added.

Figure 2 shows the standard terminology and concepts of root cause analysis that apply to difficult large-scale social problems. The conceptual organization of Figure 2 encourages asking the right WHY questions. The strategy is to first learn from the past to construct the superficial layer. WHY did past solutions fail? That leads to the intermediate cause, confirmed by identification of the low leverage point and the superficial solutions that seemed promising, but have failed to solve the problem. Next one asks WHY does the intermediate cause occur? What is its deeper cause? That line of questioning will lead to penetration of the hard-to-see fundamental layer, where the root causes may be found. Resolving the root causes by pushing on high leverage points with fundamental solutions will initiate the desired mode change, causing the system to escape lock-in to the present undesired mode and rapidly self-evolve to the desired mode of behavior.

The central role of lock-in in the environmental sustainability problem has long been noted, most famously by Hardin (1968): "Each man is locked into a system that compels him to increase his herd without limit—in a world that is limited." In difficult large-scale social problems (defined as those where serious solutions have failed for 25 years or more and involve political systems with millions or billions of people), some portion of the human system is locked into an undesirable mode and is unable to easily change to the desired mode. Lock-in occurs due to the unrelenting strength of a problem's dominant feedback loops. The desired mode change requires reengineering the system's feedback loop structure such that when force F is applied, a new root cause force R is created, and the system's current dominant feedback loops are replaced by new ones, causing the mode change to occur.

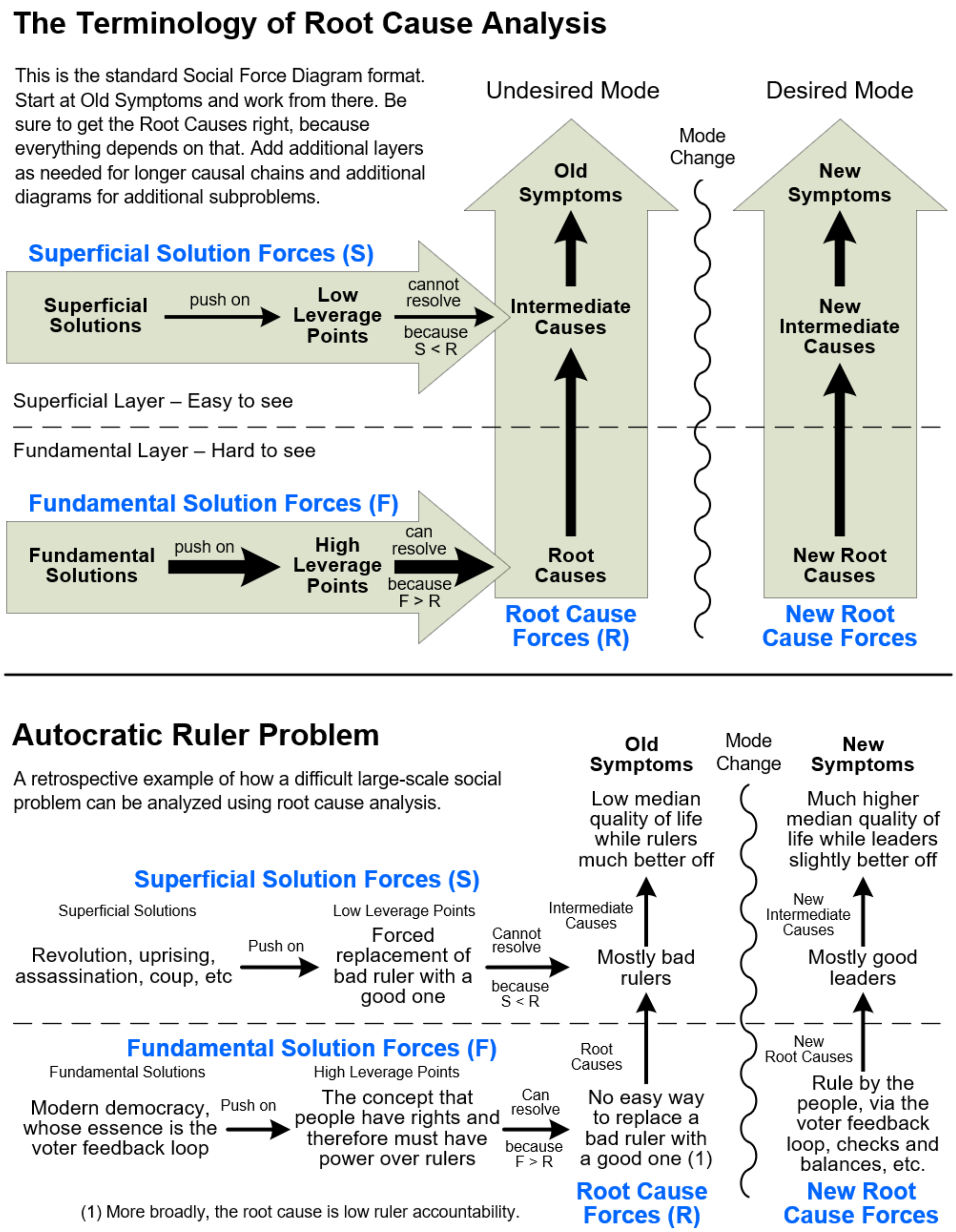

Figure 2. The standard terminology of root cause analysis and an illustrative example. Use of standard terminology and the diagram organization shown greatly facilitates model construction. The diagram identifies a problem's essential causal structure using what we call Social Force Diagrams.

Necessary Tool – Problem decomposition into subproblems

On the surface, this tool is the simplest. Yet in our analysis of the sustainability problem, it made the greatest difference of all. Without proper decomposition the problem was impossible to analyze, since difficult problems usually arise from multiple root causes. Each subproblem contains one or more root causes. Without proper decomposition, the analyst falls into the trap of unknowingly attempting to analyze multiple problems and their root causes all at the same time. This is as impossible as simultaneously conversing with three different people speaking three different languages. The human mind cannot fathom that level of complexity.

The most efficient approach to problem decomposition is standard subproblems. For example, industry uses standard groups and fishbone diagrams:

The four Ps of marketing: Product, Place, Promotion, Price (McCarthy, 1960).

The original four Ms of manufacturing: Materials, Methods, Machines, Measurement (Ishikawa, 1986, p. 19).

The nine Ms of quality control: Markets, Money, Management, Men, Motivation, Materials, Machines and mechanization, Modern information methods, Mounting product requirements (Feigenbaum, 1991, p. 59).

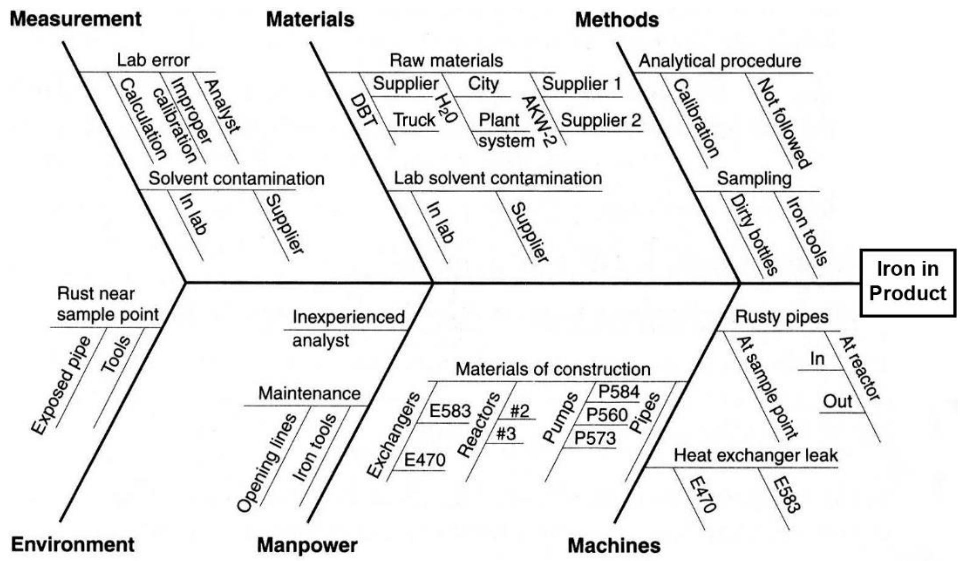

Figure 3. Fishbone diagram example using standard subproblems. Use of problem decomposition is so common in root cause analysis that fishbone diagrams are used for rapid analysis and to create simple causal diagrams. (Tague, 2005, p. 248)

For difficult large-scale social problems, we found the minimum standard subproblems to be:

1. **The original problem**. Such as environmental sustainability or climate change.
2. **How to overcome systemic change resistance**. If serious solution efforts have failed repeatedly and the problem is solvable, then high systemic change resistance must be present. *Systemic* means "originating from the system in such a manner as to affect the behavior of most or all social agents of certain types, as opposed to originating from individual agents." (Harich, 2010) Change resistance differs from policy resistance (Sterman, 2000, pp. 5–12). Change resistance refers to resistance to proposed solutions, while policy resistance refers to resistance to implemented solutions. We argue that on difficult large-scale problems like sustainability, change resistance is by far the most important type of resistance.
3. **How to prevent problem recurrence**. Difficult problems tend to recur unless a strong recurrence prevention function is present. After initial solution success, "don't be too hasty to declare victory. The last battle has yet to be fought. The battle against creeping disorder, the battle against entropy. The battle to ensure the gains you made are

permanent" (Pyzdek, 2003, p. 649). This is also known as the process control function and is not covered in this paper.

The WorldChange model

Model purpose and change resistance layer architecture

This paper extends a previous work (Harich, 2010), which found that systemic change resistance is the crux of the environmental sustainability problem and must be solved first, by resolving the root causes of that resistance. Systemic change resistance runs so high that the world's nations have been unable to overcome that formidable barrier, one result being that the SDGs and the Paris Agreement goals are voluntary. On the climate change crisis, UN Climate Change (2021) reports that, as of February 2021 the projected reduction of countries total emissions will be less that -1% in 2030 compared to 2010. The IPCC found that meeting the maximum rise goal of 1.5 degrees Celsius requires a reduction of -45%, indicating very high change resistance. In a talk celebrating the 40th anniversary of *The Limits to Growth*, Jorgen Randers presented a telling slide: "The root cause of current [solution] delays: We know the solution. But we don't like it" (Smithsonian, 2012).

This resistance must be modeled. To illustrate in a simple manner how this may be done, we have extended the World3_03 model from the third edition of *The Limits to Growth* (Meadows et al., 2004).

The lower large box in Figure 4 shows how present ISMs assume (and hope) proposed policy changes will be implemented. These models are basically highly integrated IPAT equation models (Chertow, 2001). The IPAT paradigm lacks any concept of change resistance. Consequently, so do current ISMs. This behavior can be added with a change resistance layer.

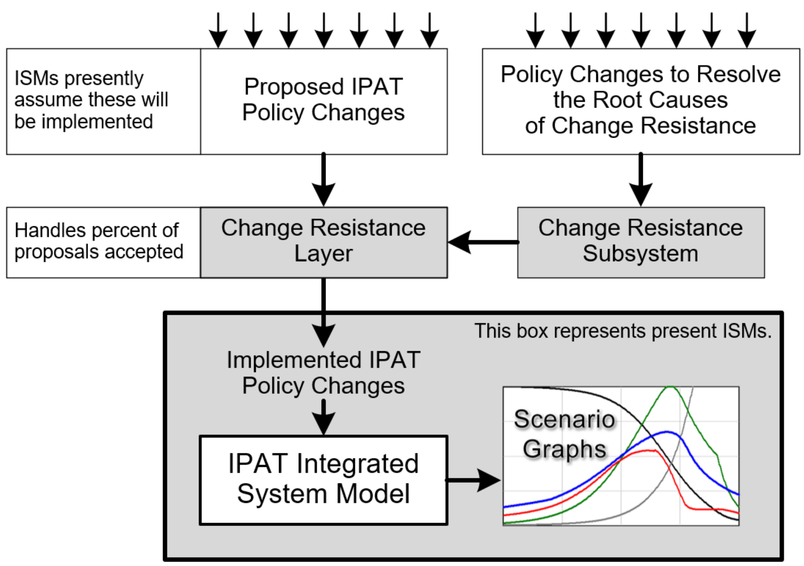

Figure 4. How the change resistance layer works.

For scenario inputs, present ISMs have only those shown on the diagram as *Proposed IPAT Policy Changes*. Addition of a Change Resistance Layer and a Change Resistance Subsystem allows a second set of inputs: *Policy Changes to Resolve the Root Causes of Change Resistance*. Once the root causes are resolved, systemic change resistance will switch from high to low, the system will accept a high percentage of *Proposed IPAT Policy Changes*, and *Scenario Graphs* can realistically show how much of the problem is solved.

Problem decomposition and root cause analysis

Recall that the RCA-based ISM process of Figure 2 uses these steps:

1. Original problem definition
2. Problem decomposition
3. Root cause analysis
4. Integrated System Model Construction
5. Successful application of system dynamics to the sustainability problem

For ISMs, Forrester's World2 model defined the problem as how the human system can flourish within *The Limits to Growth* imposed by the greater system it lives within, the environment. Forrester saw the "primary cause" of the world's *problematique* as being exponential growth in population and the use of energy and resources (Meadows, 2007). Consequently, unsustainable growth from an IPAT perspective is what World2, World3, and all subsequent ISMs have modeled. This work used only steps 1 and 4 of the process.

However, by adding steps 2 and 3 we have concluded that is *not* the primary cause. The additional steps led to a potent why question: WHY are popular solutions failing? This led to discovery of systemic change resistance as a distinct and separate problem to solve, allowing focused RCA of the *How to overcome change resistance* subproblem. The main root cause, *low political truth literacy*, explains that change resistance is high because politicians can successfully deceive voters into voting against their own best interests, and instead voting for politicians representing powerful special interests, particularly large for-profit corporations (aka *Corporatis profitis*) and their owners, the rich. The result is that special interests rather than common good interests have mostly controlled the world's democratic systems. This behavior is well documented (Beder, 2006, 2002; Korten, 2015; Shamir, 2005).

Then we asked WHY are special interests so relentlessly motivated to exploit the power of change resistance? What can explain this?

This led to discovery of an additional subproblem: *How to achieve life form proper coupling*. Proper coupling occurs when the behavior of one system affects the behavior of other systems in a desirable manner, using the appropriate feedback loops, so the systems work together in harmony in accordance with design objectives. For example, if you never got hungry you would starve to death. You would be improperly coupled to the world around you. In the environmental sustainability problem, the human system has become improperly coupled to the greater system it lives within: the environment.

The main root cause of this subproblem is mutually exclusive goals between the two dominant life forms in the human system, *Corporatis profitis* and *Homo sapiens*. *Corporatis profitis* is dead set against solving the environmental sustainability problem and is winning, because of its overwhelming control of the human system, superior financial power compared to mere citizens, and its obsessive goal of short-term profit maximization. This goal conflicts with the goal of *Homo sapiens*, which is the long-term optimization of quality of life for people. These goals are mutually exclusive.

Because *Corporatis profitis* dominates the system and drives capitalism, its goal prevails and has become *the wrong implicit goal of the system*. Peter Senge (1990, p. 88) warns us that when this occurs, “The resistance is a response by the system, trying to maintain an implicit system goal. Until this goal is recognized the change effort is doomed to failure.” Donella Meadows (2008, p. 113) phrases her warning differently: “Such resistance to change arises when goals of subsystems are different from and inconsistent with each other.”

The causal structure of these two subproblems was analyzed as shown in Figure 5. Highlights are the intermediate causes and the low leverage points that popular solutions have been pushing on (in vain), and the root causes and the high leverage points for resolving them.

The key insight is subproblem B causes subproblem A, which prevents solution of the original problem. Both subproblems must be solved before proposed solutions to the original problem will be mostly accepted.

The key good news is that no serious large-scale solutions have ever pushed on the high leverage points, since attention has been attracted to low leverage point solutions. If this hypothesis is sound, then the sustainability problem is solvable and can be solved considerably faster than presently assumed.

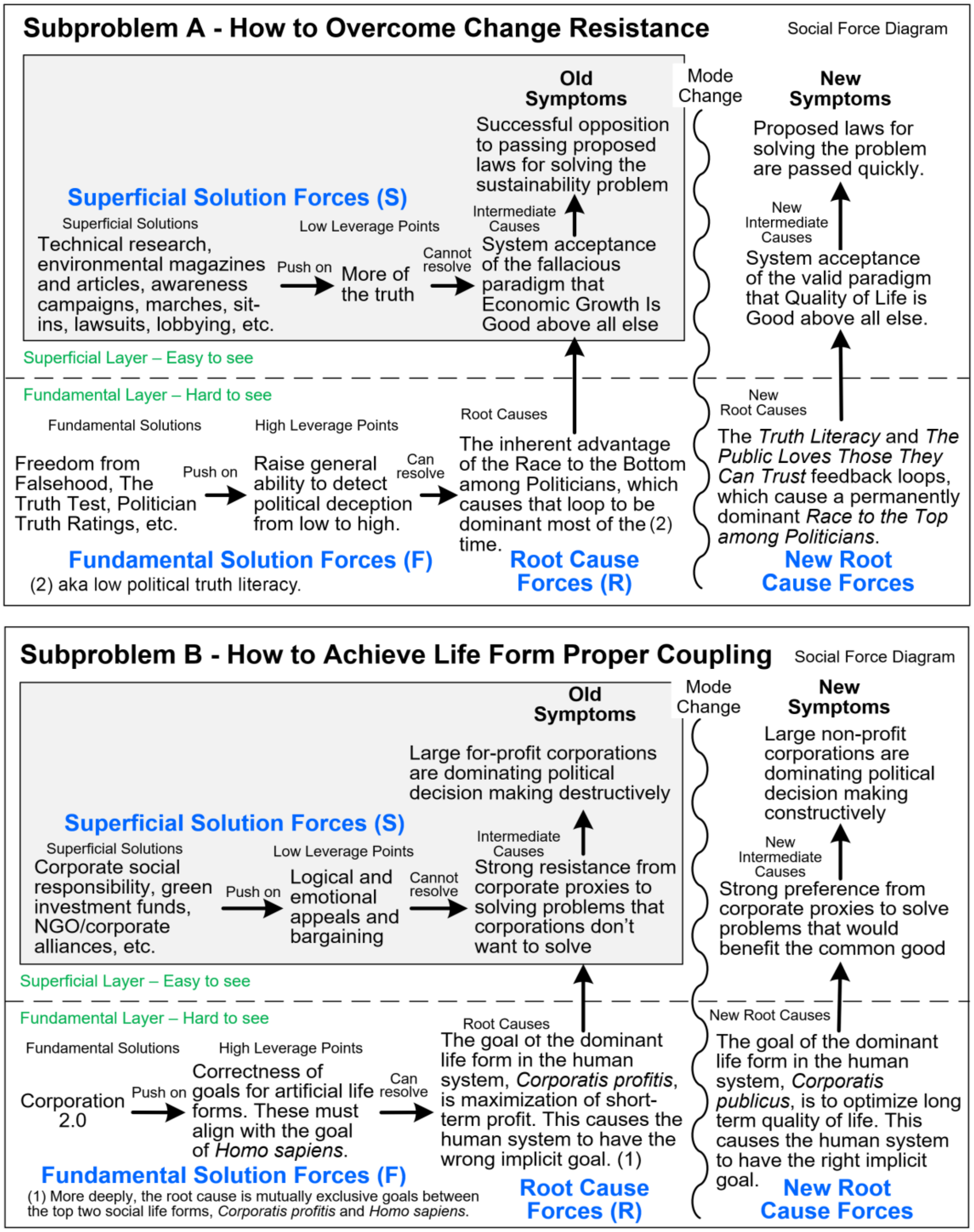

Figure 5. Social force diagrams for the two subproblems. The two gray boxes are all that environmentalists can presently see, which leads to superficial solutions.

Reflecting later on the birth of World3, Donella Meadows (2007) wrote that: (italics are in the original)

> [Because] Aurelio Peccei …was worried about what he saw, he pulled together a group of distinguished friends for a meeting in Rome in 1968. The loose network they founded was named the Club of Rome after the place of its first meeting. The job they took on was to define what they called the world's *problematique*.
>
> By 1970 the Club of Rome had expanded to 75 members and had extended the *problematique* to 66 "Continuous Critical Problems." Poverty, war, pollution, crime, oppression, resource depletion, terrorism, economic instability, racism, and drug addiction

> were on the list. The Club was made up of problem solvers, men of action. They wanted more than a list of problems, they wanted *solutions*. How to tackle this nest of woes? Presumably the problems are interrelated, but how? Are there fundamental underlying causes [which RCA calls root causes] that can be dealt with, without having to take on each problem separately?

According to root cause analysis, yes. The systemic change resistance emanating from the root cause of subproblem B applies to any problem whose solution would benefit the common good and not the uncommon good of *Corporatis profitis*. It thus applies to the entire *problematique*. The pattern in the "nest of woes" problems is *Corporatis profitis* has no motivation to solve them, and in fact is motivated to *not* solve many of them. War and preparing for it is highly profitable. So are the bubbles and long run-ups to recessions, and the resulting government bailouts of large firms. So is poverty, because then *Corporatis profitis* and the rich have more. So is pollution, because that externalizes large costs. And so on.

Therefore, we can logically anticipate that once ISM builders revise their models to include the two subproblems (or something like them) and switch to model design and scenarios based on resolving root causes, the policies generated for solving the subproblems will lead not only to the human system "wanting" to solve the environmental sustainability problem as much as it doesn't want to solve it now. It will also lead to the system wanting to solve any problem whose solution would benefit the goal of *Homo sapiens*, which includes the entire "nest of woes" of the global *problematique*. If the main root causes of the two subproblems presented here (and additional root causes identified by ISM builders) are reasonably correct and can be resolved by policies generated by models built by thoughtful adherence to the principles of good system dynamics, that outcome is not fantasy. It is a practical meta-solution strategy, built one brick at a time by applying the tools of RCA and problem decomposition, just as the business world has done for a century. This should serve as some indication of the potential transformational power of RCA-based ISMs.

Submodel: The Change Resistance Subsystem

A Vensim version of World3_03 was modified in 2008 so that the *scenario* slider (not shown) controls behavior of the changes required to run World3 scenarios 1 to 10. This makes it *much* easier to work with World3. Harich gave the model to Bob Eberlein (Then working at Ventana Systems. Bob was the wizard behind Vensim, our favorite system dynamics modeling software.), who improved the modification by adding the Scenario Inputs page and putting the *scenario* node there, along with its effect on model nodes.

Analysis of the two subproblems produced a system dynamics model of *The Dueling Loops of the Political Powerplace*. The model was simplified and incorporated into World3 in 2013 on a separate page. In 2021, after the Truth Literacy Training study (discussed later) was complete and its implications understood, the submodel was further improved. After removing 17 less significant nodes for clarity (all were constants except for Time), the current submodel is shown in Figure 6.

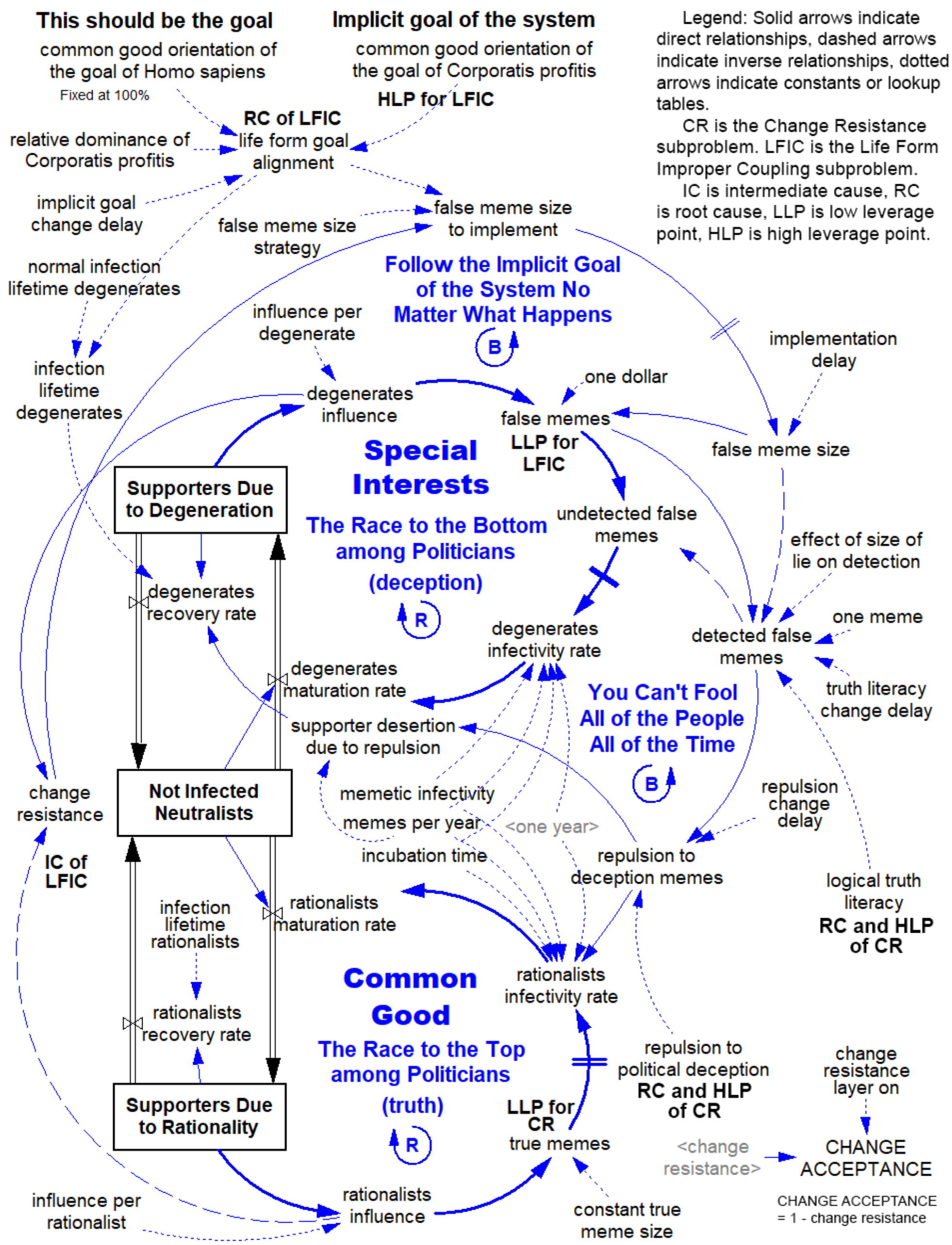

Figure 6. The change resistance subsystem, with key causal nodes identified. Scenarios 5 to 8 push on the 3 high leverage points.

The actual submodel hookup was made by inserting the CHANGE ACCEPTANCE node in the 12 places where World3's scenario solutions changed model behavior. Acceptance ranges from zero to 100%. World3 equations were edited such that the amount of acceptance determines the amount of the change implemented, thereby mimicking real world behavior.

Figure 5's causal diagram for the change resistance subproblem identifies problem symptoms as "*successful opposition to passing proposed laws for solving the sustainability problem*." WHY does that occur? We found the main intermediate cause to be "*system acceptance of the fallacious paradigm that Economic Growth Is Good Above All Else*." Herman Daly, referring to his reading of *The Limits to Growth* in 1972, wrote that "it is now forty years later and economic growth is still the number one policy goal of practically all nations; that is undeniable" (Randers, 2012, p. 73). Jacobs (1996, p. 117) found that "Over the last 50 years, growth has become the main objective of politics, regarding not just as the source of wealth creation, but as the automatic solution to all other problems."

Continuing to trace the causal diagram, the reaction of environmentalists has been to attempt to resolve the intermediate cause with a "*more of the truth*" strategy. This strategy is implemented with solutions like "*technical research, environmental magazines and articles, awareness campaigns, marches, sit-ins, lawsuits, lobbying, etc*."

Despite leading to much new environmental legislation at the national level and a string of international summits on environmental sustainability and climate change, these solutions have largely failed. WHY? Because they are superficial solutions pushing on a low leverage point to resolve an intermediate cause. WHY has the fallacy that Economic Growth Is Good Above All Else become so universally accepted? By employing system dynamics, we found the main root cause was "*the inherent advantage of the Race to the Bottom among Politicians, which causes that loop to be dominant most of the time."*

Model structure centers on a perpetual duel between the Race to the Top versus the Race to the Bottom. This captures a particular aspect (power based on use of political deception versus the truth) of the left/right political spectrum. This must be done, since "global politics is first and foremost a debate between the left and the right," where the left favors equality and the right favors inequality via hierarchy and preservation of the power status quo (Noel and Therien, 2008, p. 3). Capturing this tension adds significant realism to the model, as "Power dynamics are critically important in decision making, particularly when it comes to formulating and implementing policies supported by system dynamics modelling. According to Houghton, any true systemic approach needs to include issues of politics, power or coercion because they impact the area of concern" (Cavana et al., 2019).

"The central problem facing conservatives, once their country's [voting] franchise had been extended to include most adult men, was that it was unclear why most voters would want to vote for them" (Ware, 1996, p. 32). If a conservative politician cannot appeal to voters on the basis of the truth, the only alternative is deception. Successful deception allows manipulative politicians (working on behalf of entrenched powerful special interests) to deceive a majority of voters into voting against their own best interests. Jeremy Bentham, the father of utilitarianism, in his handbook of political fallacies published in 1824, describes the practice: "…it is impossible by fair reasoning ...to justify the sacrifice of the interests of the many to the interests of the few.... It follows that for effecting this purpose they must have recourse to every kind of fallacy, and address themselves, when occasion requires it, to the passions, the prejudices, and the ignorance of mankind" (Larrabee, 1925, p. xxi).

The Race to the Bottom's inherent advantage occurs because the size of a falsehood (and hence its attractive power) can be inflated, but the size of the truth cannot. A politician can tell a bigger lie, like budget deficits don't matter. But they cannot tell a bigger truth, such as I can balance the budget twice as well as my opponent, because once a budget is balanced, it cannot be balanced any better. From a mathematical perspective, the size of a falsehood can be inflated by saying that 2 + 2 = 5, or 7, or even 27, but the size of the truth can never be inflated by saying anything more than 2 + 2 = 4. Inflation is used to create fear when there is nothing to fear, doubt when there is nothing to doubt, the false promise of I can do so-and-so for you when I really cannot, a large flaw in one's opponent when there is only a small flaw, and so on.

In the Race to the Bottom, deceptive politicians use *undetected false memes* to infect *Not Infected Neutralists*, causing them to become *Supporters Due to Degeneration*. (Model nodes are italicized in this paper.) In the Race to the Top, truth-telling politicians do just the opposite, by using *true memes* to infect neutralists, thus increasing *Supporters Due to Rationality*.

Because the size of a falsehood can be inflated (by telling a lie) but the size of the truth cannot be inflated, the Race to the Bottom contains an inherent advantage and is the dominant loop most of the time in the world's political systems. We know this to be so because of such strong prolonged change resistance to solving common good problems like sustainability, including the entire *problematique* "nest of woes." Thus, the main root cause of successful change resistance is "*the inherent advantage of the Race to the Bottom among Politicians, which causes that loop to be dominant most of the time*." The inherent advantage of the Race to the Bottom only exists if political truth literacy is low, so a shorter term for the root cause is "*low political truth literacy."*

It follows that the high leverage point for resolving the root cause is "*raise general ability to detect political deception from low to high."* The analysis developed nine sample solution elements for doing this, such as "*Freedom from Falsehood, The Truth Test, Politician Truth Ratings, etc."*

The Truth Literacy Training Study

Good system dynamics and RCA require testing of all key assumptions. How much confidence can we have in the assumption that political truth literacy is low and can be raised to high in a practical manner, which forms the bedrock of the change resistance model?

To answer this question the Truth Literacy Training study was run using a Prolific online panel and our own software for the questionnaire. 93 US subjects (age range 22 to 51, average age 31, 49% male) were randomly assigned to three groups. Group 1 received training on a neutral topic. Group 2 received training on how to tell if a political claim (embedded in a political statement) was true or false, by spotting the pattern of fallacy or non-fallacy used. Group 3 received the same training as group 2 plus training on how to vote correctly (given the perceived level of truth of a claim) by applying two rules: Reward the Truth Teller and Penalize the Deceiver. Figure 7 summarizes study results.

Political truth literacy contains two components: logical and vote. *Logical truth quotient* (LTQ) is the ability to logically tell if a deceptive claim is true or false, and was measured by the percent correct for the truth questions for deceptive statements. *Democratic truth quotient* (DTQ) is the ability to vote correctly given a deceptive statement made by a politician, and was measured by the percent correct for the vote questions for deceptive statements. DTQ measures voting truth literacy, while LTQ measures logical truth literacy. Deceptive statements contained

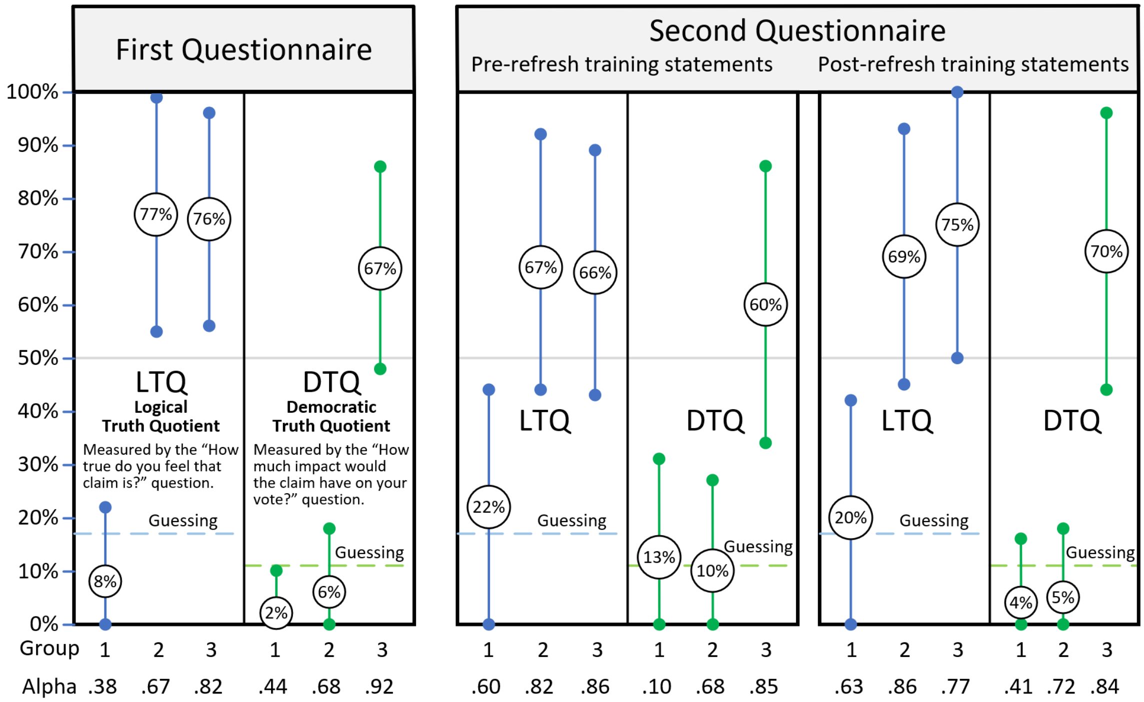

Figure 7. Results of the Truth Literacy Training study. Average scores and 95% confidence intervals for answers to deceptive statements are shown, with guessing levels and Cronbach's alpha. Treatment groups were:

1 – Trained on neutral topic
2 – Trained on claims
3 – Trained on claims and vote

seven fallacies we found common in political appeals: cherry picking, flawed application of the Strong Evidence Rule, ad hominem attack, appeal to emotion, strawman, false dilemma, and false fact lie.

LTQ is naturally low, at 8% for group 1. Voters not trained in logical truth literacy can spot a fallacy in a deceptive political statement an average of only 8% of the time. DTQ is also naturally low, at 2% for group 1. Both are crucial findings and appear to explain why change resistance to solving common good problems, including sustainability, is so stubbornly high. While the study cannot say 8% and 2% are accurate measures, we feel the results indicate political truth literacy is low instead of medium or high.

DTQ for group 2 was 6%, a deeply counterintuitive discovery. We expected it to be low, but not that low. The 6% means that even if voters have been trained on how to tell if a deceptive claim made by a politician is true or false, they are unable to correctly translate that knowledge into how to vote correctly. Group 2, which received claim training but not vote training, averaged spotting deception 77% of the time, but could translate that knowledge into voting correctly only 6% of the time. The claim training made almost no difference on voting correctly. This is why the vote training of group 3 is required.

The key data is DTQ for groups 1 and 3. The large increase, from 2% to 67%, a 65-point rise, suggests that Truth Literacy Training and other solution elements will be capable of resolving much of the root cause of change resistance: low political truth literacy. Group 3 training took only about one hour, indicating that Truth Literacy Training, such as in education systems and online training, will not require that much of a person's time.

A follow up study 26 days later using different statements found DTQ for group 3 had declined from 67% to 60%, a 7-point fall. After an average of 30 minutes of refresh training, DTQ for group 3 rose to 70%, indicating regular refresh training of some type can work and will be required. Or it may be that like reading and writing literacy, once truth literacy matures and becomes the reasoning default and is exercised often enough, little decline will occur.

However, LTQ for group 1 was 22% and 20% for the pre-refresh and post-refresh training statements, versus 8% for the first questionnaire. This indicates spotting deception was substantially easier in the second questionnaire statements, and suggests there was more than the 7-point decline noted above and that the refresh training may not have worked as well as the 70% indicated. The second questionnaire statements were developed after the first questionnaire was run. Without realizing it, we structured them slightly differently and frequently omitted stating how strongly supported the premises were. This caused the second set to be substantially easier than the first set, as it made fallacies easier to spot. This problem is easily corrected.

Truth Literacy Training employs the preemptive aspect of inoculation theory using fallacy pattern recognition instead of misinformation correction as in fact checking (Cook et al., 2017). Our approach goes one step further than Cook's by introducing vote training and improves training effectiveness by adding a catalog of common fallacies and the Personal Truth Test. This approach can nullify the deceptive power of motivated reasoning, a well-established theory explaining how political decision-making works. "In short, citizens are often partisan in their political information processing, motivated more by their desire to maintain [often false] prior beliefs and feelings than by their desire to make 'accurate' or otherwise optimal decisions." (Lodge and Taber, 2013, p. 149)

The hypothesis that political truth literacy is currently low and can be fairly easily raised from low to high was supported.

Causal points in the Change Resistance Subsystem

The main root cause of the change resistance subproblem is modeled by the *logical truth literacy* and *repulsion to political deception* nodes. These two nodes capture the logical and vote aspects of political truth literacy, as discussed in the study. When both are low, the root cause force of these two nodes causes the Race to the Bottom to be the dominant loop most of the time. The high leverage point is to raise both from low to high.

Environmentalists, however, have not been pushing on these high leverage points. Their solutions have been directed toward the low leverage point of *true memes*. Unlike *false memes*, these have a *constant true meme size* of one. Because pushing here cannot significantly inflate the attractive power of the truth and does nothing to resolve the root cause, it cannot resolve the intermediate cause of "*system acceptance of the fallacious paradigm that Growth Is Good above all else*," not shown on the model.

The intermediate cause of the life form improper coupling subproblem is "*strong resistance from corporate proxies to solving problems that corporations don't want to solve*." This is modeled in the *change resistance* node, which equals *degenerates influence / (degenerates influence + rationalists influence)*.

The main root cause of the life form improper coupling subproblem is "*mutually exclusive goals between the top two social life forms, Corporatis profitis and Homo sapiens.*" This root cause is captured in the *life form goal alignment* node. As discussed earlier, *Corporatis profitis* so dominants society that its goal is the implicit goal of the system. This dominance is measured by the *relative dominance of Corporatis profitis* node, whose value is 90%. Using relative dominance as goal weight, we arrive at this important equation:

```
life form goal alignment = common good orientation of the goal of Homo sapiens *
( 1 - relative dominance of Corporatis profitis ) + common good orientation of the goal of
Corporatis profitis * relative dominance of Corporatis profitis
```

The common good orientation of the goal of *Homo sapiens* is fixed at 100%. That of *Corporatis profitis* is initially 20%. This leads to an initial value of 28% for *life form goal alignment*, which is low.

The high leverage point for resolving the root cause is clear: change the goal of *Corporatis profitis* to be much more in alignment with the goal of *Homo sapiens*.

Change resistance behavior arises endogenously from the structure of the change resistance subsystem. The model was tuned to give realistic behavior using constant and lookup table estimates, since this data has never been measured, particularly on a global scale. This satisfies the purpose of the exploratory model: to identify and demonstrate behavior of the root cause forces behind systemic change resistance.

High leverage point scenarios

These demonstrate how adding a change resistance layer to ISMs gives significantly more realistic behavior and can lead to more productive policy insights. The eleven scenarios are displayed in Figures 8 and 9.

Unlike the three editions of *The Limits to Growth* which ran the model from 1900 to 2100, the scenarios presented here run from 1900 to 2200. Forty-nine years have passed since the first version of World3 in 1972. Long term system behavior is impossible to determine without a one century extension. While World3 was not designed for this extension and Dennis Meadows has cautioned Harich on this practice, its behavior holds up quite nicely for our purpose, indicating how well built the model is.

Scenario 1. This duplicates scenario 2 of the World3 model. The result is collapse sometime between 2000 and 2100. This "business as usual" scenario (and similar scenarios generated by other ISMs) is widely seen as the problem to solve.

To be conservative on such an important estimated parameter, World3 scenario 2 begins with twice the *nonrenewable resources* of scenario 1. Scenario 2 rather than 1 is seen as the problem to solve because that's what the three editions of *The Limits to Growth* have done. All use scenario 2 as their starting point for subsequent scenario-based attempts to solve the problem. Rather than a solution starting in 2002, scenario 2 is a change to initial model parameters. Scenario 2 is the de facto reference mode for World3.

Scenario 2. This duplicates scenario 9 of the World3 model. Solution policies were applied in 2002. Collapse is avoided, with a long, apparently sustainable high level of *population* and *human welfare index*. However, examine the *nonrenewable resources* curve. Its downhill trend indicates collapse has only been postponed. World3 scenario 9 is used in all the following scenarios.

Scenario 3. The change resistance layer is turned on. *Now the model exhibits realistic behavior*. Because of high systemic change resistance to solution policies, only 20% are implemented. The result is collapse, though it's not as severe as scenario 1 because 20% of the policies were implemented. This *was* the problem to solve in 2002, the solution start year used in the 2004 version of the World3 model (Meadows et al., 2004).

Scenario 4. Reference Mode. However, we are now in 2021. Solutions and change resistance alleviation policies cannot be implemented immediately. If the call to action begun in the three editions of *The Limits to Growth* and repeated in countless publications like this paper is finally taken seriously, the earliest they could start is two years from now. This scenario thus moves the solution start year from 2002 to 2023. *This is the real problem to solve* and serves as our reference mode. Note how the collapse is significantly larger than scenario 3, as seen in the *population* and *food* curves.

To reflect that change resistance is currently high, the initial values for *repulsion to political deception*, *logical truth literacy*, and *common good orientation of the goal of Corporatis profitis* are all low, at 20%. The model is tuned so that *change resistance* is initially 80%. This causes *CHANGE ACCEPTANCE* to initially be 20%, which allows only 20% of the effect of World3's scenario 9 parameter changes to pass through to model behavior. Given the low amount of progress made on implementing solutions to the global environmental sustainability problem, especially climate change, this approximates actual system behavior. *Near-term collapse is probable and we see no realistic way to avoid it*, with a possible exception. But the amount of collapse can be reduced and the final outcome greatly improved if change resistance can be fully overcome.

The exception would be if the effect of pushing on high leverage points, such as those shown here, can somehow be radically accelerated. This is critical, since World3 contains no equivalent of the ecological tipping points that will soon be triggered by the effects of climate change.

Scenario 5. Now that we've created our reference mode, we can show the effects of pushing on the two high leverage points associated with change resistance. This scenario pushes on a high leverage point for resolving the root cause of the change resistance subproblem, by raising *logical truth literacy* from 20% to 50%.

As expected, *change resistance* falls some. But it falls slowly. Population collapse is not avoided, but a population rebound appears as reduced change resistance takes effect. Quite worrisome is this rebound reduces nonrenewable resources dramatically.

Scenario 6. This scenario rolls back the increase in *logical truth literacy* to what it was before, 20%, and pushes on the other high leverage point associated with change resistance. *Repulsion to political deception* is raised from 20% to 50%. The result is similar to scenario 5, though the reduction in *change resistance* is considerably less. This indicates *logical truth literacy* has higher leverage.

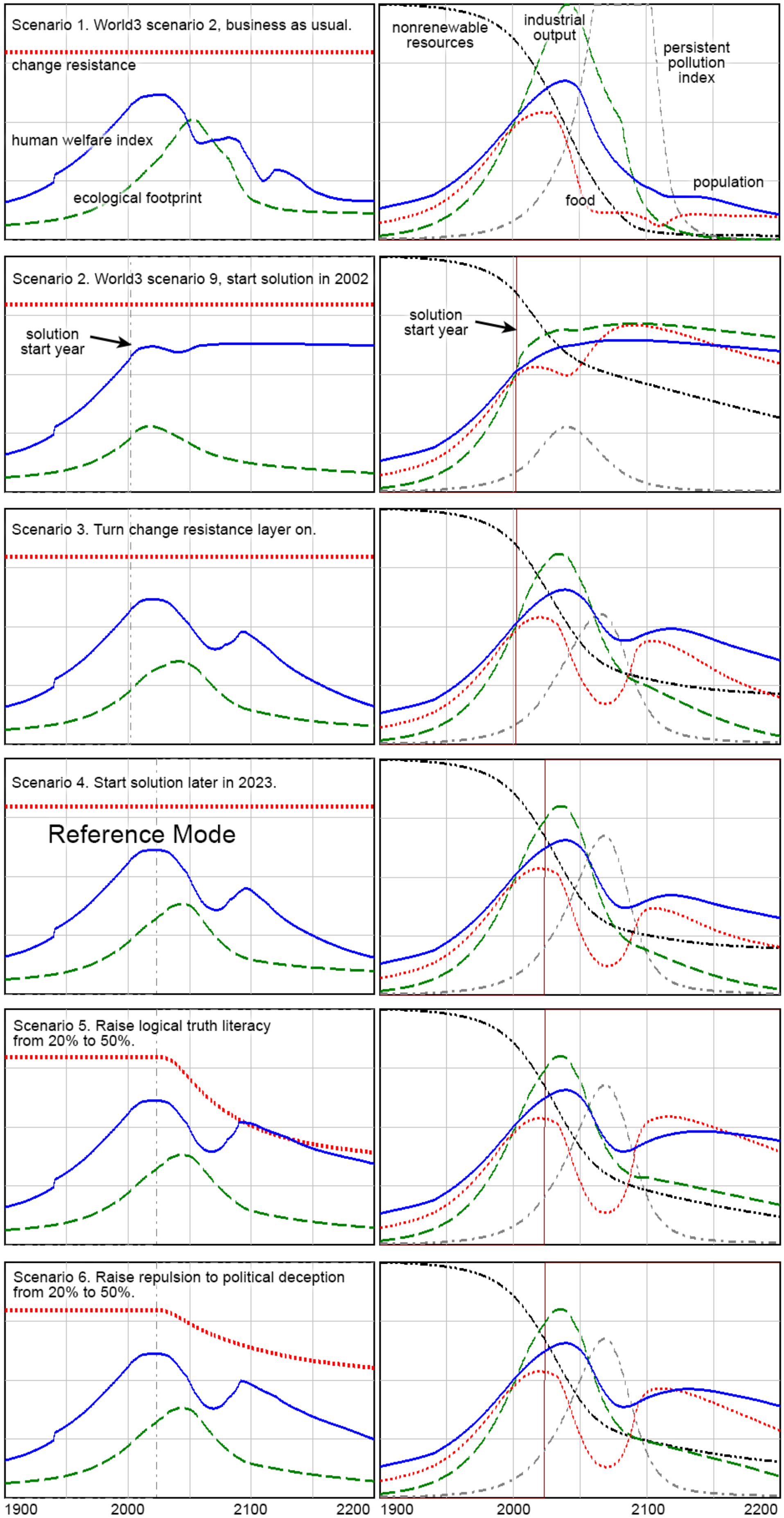

Figure 8. Scenarios 1 to 6.

Scenario 7. The Truth Literacy Training study provides empirical evidence that *both* change resistance subproblem high leverage points must be pushed on to raise political truth literacy from low to high. This scenario does that by raising *logical truth literacy* and *repulsion to political deception* from 20% to 50%, which raises them from low to medium. We would like to raise them to high, but prefer a conservative, more achievable scenario.

The result is a much faster and larger reduction in *change resistance*. Population collapse still occurs, but collapse is smaller and population rebound is slightly higher. The *human welfare index* rebounds fully, a happy result.

However, new ominous behavior has appeared. *Food* and *industrial output* encounter catastrophic collapse around year 2150 (this is not an exact prediction). This is triggered by *nonrenewable resources* depletion. Higher *industrial output* has caused higher resource use over such a long period of time that the depletion effect built into World3 now appears. (What a wonderfully robust model!) Once *nonrenewable resources* fall to 10%, the cost of further resource extraction soars exponentially. Our central scenario planning question now becomes how can we avoid catastrophic collapse due to nonrenewable resource depletion?

Scenario 8. Scenario 7 resolved the root cause of the change resistance subproblem. With that subproblem solved, the human system can now realistically resolve the root cause of the life form improper coupling subproblem, which this scenario does by pushing on the high leverage point of raise the *common good orientation of the goal of Corporatis profits*. This scenario raises that from 20% to 60%. We avoid raising it higher to follow the rule that estimated model parameter should be conservative rather than optimistic, though we suspect all three high leverage points can be raised higher than done in these scenarios. Since it will take time for scenario 7 to take effect and allow scenario 8, the change in *life form goal alignment* has a 10-year delay.

Change resistance now falls slightly faster. More importantly, *it falls eventually to zero.* While this scenario still does not solve catastrophic collapse caused by the all-important nonrenewable resource depletion problem, it opens the door to further scenarios that could. These are impossible in today's world due to high change resistance. But in the WorldChange model, where the root causes of systemic change resistance are modeled and resolved, they now become tantalizingly possible. Examples are explored in scenarios 9, 10, and 11. These three scenarios start in 2033, since transition from high to low systemic change resistance will take time.

Scenario 9. Bowing to the insights of Thomas Malthus and the IPAT equation, this scenario reduces *total fertility* from about 2 to 1.3 children per family. The 1.3 is what the population growth program in China achieved in 2004 in urban areas and compares favorably to rates of 1.04 in Singapore, 1.38 in Japan, and 0.91in Hong Kong (Hesketh et al., 2005), as well as 1.32 in Cyprus, 1.35 in Greece, 1.26 in Spain, and 1.29 in Italy (EurostatFertility, 2020). The population collapse problem is solved. Instead, a managed population decline occurs, which reduces resource depletion enough that the catastrophic collapse of scenarios 7 and 8 is avoided.

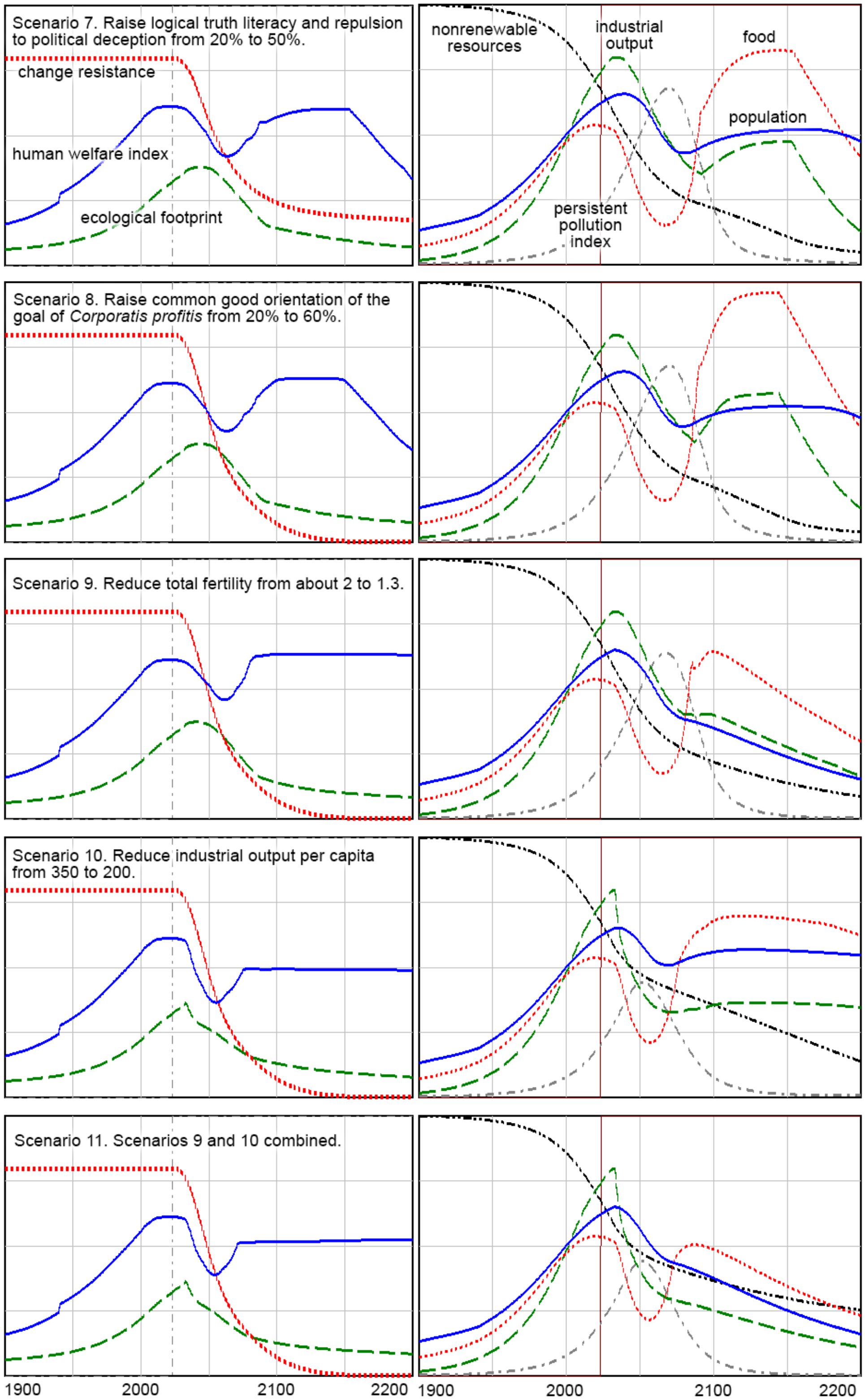

Figure 9. Scenarios 7 to 11.

A managed population decline differs entirely from population collapse. In a managed decline, population falls due to voluntary reduction of average family size (a pleasant world, where quality of life and *joie de vivre* reign supreme), rather than falling due to starvation and conflict (a dystopian world, one reminiscent of the Hunger Games).

Scenario 10. Low systemic change resistance allows another scenario that was also impossible before. This scenario rolls back the change made in scenario 9. Instead, *industrial output per capita* is reduced from 350 to 200, reflecting a cultural change from a quantitative mode (which benefits *Corporatis profits)* to a qualitative mode (which benefits *Homo sapiens* and is the only sustainable path forward). "…John Stuart Mill was right, that populations of human bodies and accumulation of capital goods cannot grow forever, that at some point quantitative growth must give way to qualitative development as the path of progress" (Daly, 1996, p. 7).

This results in no population decline while also avoiding catastrophic collapse. The 200 allows a high *human welfare index* and is what *industrial output per capita* was in 1969, so this scenario involves nothing draconian. However, as in scenario 9, *nonrenewable resources* are falling fast and collapse is merely postponed.

Scenario 11. Scenarios 9 and 10 are combined. The effect is large reductions in the P and A of the IPAT equation. The T was already drastically reduced by World3 scenario 9, which cut persistent pollution by 90%.

The satisfactory result is a managed population decline and *nonrenewable resources* of about 25% in 2200 (this is not an exact prediction). While resources are still declining, the rate is slow. There is now ample time for *Homo sapiens*, working with what has become *Corporatis publicus*, to devise and implement a long-term solution to the environmental sustainability dimension of the Anthropocene.

Discussion of system dynamics versus root cause analysis

Table 1. Key differences between system dynamics and root cause analysis

Element	System Dynamics	Root Cause Analysis
1. Definition	A simulation modeling language and related practices for understanding and improving the behavior of complex dynamic systems.	The systematic practice of finding, resolving, and preventing recurrence of the root causes of causal problems.
2. Types of problems it handles well	Complex dynamic systems	Any causal problem
3. Central focus	Feedback loop structure	Root causes
4. What drives synthesis of the key abstractions	The dynamic hypothesis, created in the system conceptualization step. (Martinez-Moyano and Richardson, 2013) Tables 3 and 5.	The Five Whys. Starting at problem symptoms one asks "WHY does this occur?" until the root causes are found.
5. How it builds understanding of a problem	Construction of the feedback loop simulation model that endogenously duplicates problem behavior "for the right reasons." Problem behavior is defined by reference mode data. Complex models are summarized by causal loop diagrams.	Construction of a formal diagram of the problem's essential causal structure, supported by ways to test and explore the key assumptions, such as experimentation and simulation modeling as necessary.
6. How it finds high leverage points for policy intervention	Build a model that replicates reference mode behavior. Then by model inspection and scenario experimentation find the preferred scenario that best solves the problem.	Find the root causes. Then find the high leverage points for resolving the root causes.
7. Key output	Graphical behavior of how the model responds to solution policies and the parameter values used to elicit that behavior.	Description of the problem's essential causal structure, with emphasis on root causes and high leverage points.

Table 1 compares system dynamics and RCA. The differences explain why ISMs have failed to include the root causes of the sustainability problem. As the process in Figure 1 illustrates, this is because formal RCA is not used to drive construction of integrated models. The result is ISMs have included only the intermediate causes, due to the Superficial Solutions Trap. The table contains the reason for this claim, which has far-reaching implications.

The precise reason lies in the fourth element, "What drives synthesis of the key abstractions." *By not explicitly using RCA, system dynamics violates the RCA rule of the Five Whys.* For ISMs this has led to stopping at intermediate causes, since for many complex problems modeling intermediate causes is sufficient to reproduce reference mode behavior. This rule violation may be challenging for experienced system dynamics analysts to understand and accept, because of the strong assumption that if a model can endogenously reproduce reference mode behavior according to its dynamic hypothesis, then it must contain the "causes" of the problem. Homer and Oliva (2001) summarize this paradigm: (italics added, references preserved)

> The *dynamic hypothesis* is a cornerstone of good system dynamics modeling practice. It "explains the dynamics as *endogenous consequences* of the feedback structure" (Sterman, 2000), and explicitly states how structure and decision policies generate behavior (Richardson and Pugh, 1981a). Moreover, "The inclusion of basic mechanisms from the outset forces the modeler to address a meaningful whole at all stages of model development" (Randers, 1973). That is, a *dynamic hypothesis* is the key to ensuring that the analysis is focused on diagnosing problematic behavior and not on enumerating the unlimited details of a "system."

To explain this point further and begin paradigm change, let's review three examples where a model omits the root causes but can reproduce problem symptoms. Recall that in RCA, the Five Whys is used to build causal chains, which all follow this form:

Root Cause → Intermediate Cause(s) → Problem Symptoms

Problem 1. *A patient has a fever. The intermediate cause is infection. The root cause is a damaged immune system, which has failed to prevent the infection.*

A system dynamics model (or any model type: econometric, agent based, etc.) of the fever and infection could be easily constructed. It would endogenously show how once the infection entered the body it replicated, causing the patient's temperature to rise to the point of a fever. But if this was a case where there was a deeper cause, such as damaged immune system, then the model boundary would be inadequate and the model would omit the root cause, just as many doctors have done, when due to a faulty mental model they treated only the infection, because they failed to spot its deeper cause.

Problem 2. *On January 28, 1986 the NASA space shuttle Challenger exploded 73 seconds into flight, killing all aboard. A presidential commission was formed to investigate the disaster. Investigation quickly concluded that the cause of the explosion was O-ring failure due to unusually cold air temperature.*

However, Richard Feynman, an outsider appointed to the commission to broaden its thinking, did not stop there. NASA had policies in place that should have prevented launch on such a cold day, when air temperature was 36 degrees Fahrenheit, 15 degrees colder than any previous shuttle launch. Feynman found that engineers' warnings that it was too cold to launch had gone unheeded by management. WHY had management failed to listen to its own experts? After much digging, he concluded the root cause was that public relations (such as no more launch delays!) had a higher priority than following launch policies. Feynman summed this up in his final report: "For a successful technology, reality must take precedence over public relations, as nature cannot be fooled." (Feynman, 1986)

The commission could have built a system dynamics model showing how O-ring failure caused the explosion. In fact, their mental models did exactly that and the commission wanted to stop there. But Feynman pressed on and expanded the boundary of his mental model of the problem, until it contained the root cause. Later work by NASA led to a fundamental solution to resolve the root cause and prevent recurrence (NASA, 1986). This allows the retrospective social force diagram of Figure 10 to be constructed.

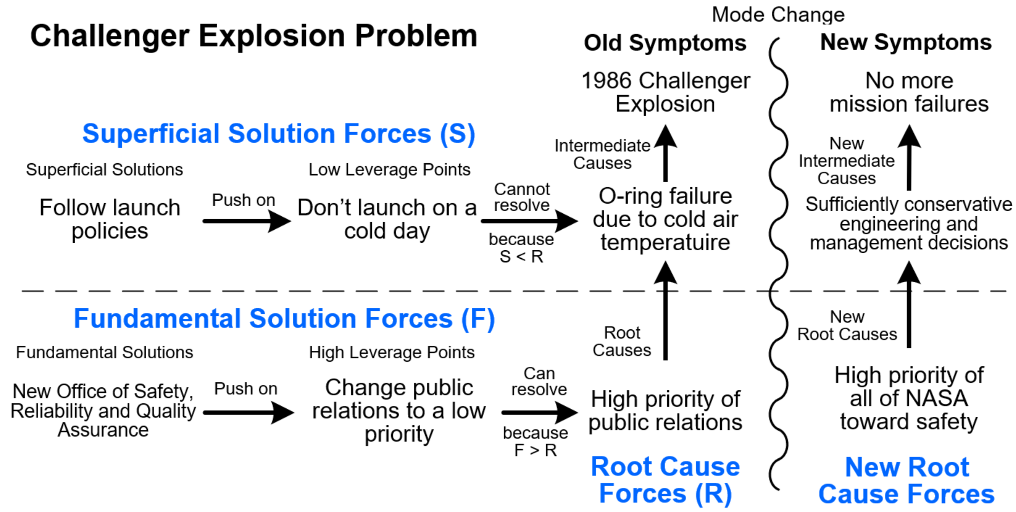

Figure 10. Social force diagram of the Challenger explosion problem. The superficial solution failed because S < R. Force S is always less than force R, because root causes exert a stronger force on intermediate causes than anything else can. The fundamental solution succeeded (temporarily) because F > R. Fundamental solutions can resolve root causes, because high leverage points allow design of solutions where F > R.

The mode change worked at first. However, the fundamental solution failed to produce a strong persistent self-managing change. The result was the *How to prevent problem recurrence* subproblem was never fully solved. As a result, the problem recurred with the space shuttle Columbia disaster in 2003. The investigation report concluded that while "the physical cause [intermediate cause] of the loss of *Columbia* and its crew was a breach in the Thermal Protection System… the organizational causes [root causes] of this accident are rooted in the Space Shuttle Program's history and culture…." (InvestigationBoard, 2003)

The point of this example is that the mental model that existed on Challenger launch day included only the superficial layer. A system dynamics model could have been built showing that NASA was operating prudently and that following launch policies would prevent O-ring failure on a cold day. The model would show that the solution of "Follow launch policies" should work. But it failed.

Problem 3. *The classic Five Whys problem of "Why did the machine stop?"* The example presented earlier contained five questions and answers. The first four answers were intermediate causes, while the fifth answer was the root cause.

It would not be hard to build a system dynamics model for each depth of analysis. The first would endogenously model the first intermediate cause. The second would model the first and second intermediate causes, and so on, as each model enlarged its boundary. Only the fifth model would have a correct boundary and include the root cause.

The three examples demonstrate the ease of building endogenous models that can replicate reference mode behavior but yet omit the root causes. Any model that excludes root causes is a superficial layer model.

It thus appears ISM modelers have fallen into the Superficial Solutions Trap. This occurs when problem solvers unknowingly assume intermediate causes are root causes, and then develop solutions based on that (false) assumption. This leads to solutions directed toward intermediate rather than root causes. The trap can be avoided by driving construction of ISM models with RCA.

Loop dominance analysis (LDA) can sometimes assist with RCA. LDA can be used to find dominant feedback loops. "...a loop that is primarily responsible for model behavior over some time interval is known as a dominant loop" (Richardson and Pugh, 1981b, p. 285). Because the Dueling Loops model is a simple system with few variables and loops, no formal LDA is necessary (Oliva, 2016), and loop dominance is easily determined by experimentation, which agrees with inspection. The advantage of identifying dominant loops is they may contain root causes or point towards them.

Sensitivity analysis can also sometimes help in finding high leverage points. In simple models like the Dueling Loops, this can be done by inspection and experimentation. More complex models may require automated sensitivity testing. The advantage of locating high leverage points with sensitivity analysis is they can provide clues leading to root causes.

Using LDA to find root causes or sensitivity testing to find high leverage points implies that model construction was not driven by RCA. This is not a good practice because it is correlation based rather than causal chain construction based, which is what the Five Whys encourage. Models constructed without formal RCA, and use of LDA and sensitivity analysis instead, will tend to have inadequate causal structure for the more difficult problems. We offer the model in this paper versus current and past ISMs as an illustrative example.

These two approaches can be useful, however, for existing models not constructed using RCA. They can also be useful when RCA drives modeling to confirm the root causes and to create a clear feedback loop dominance profile of changes in loop dominance.

Conclusions

Based on our work with root cause analysis and the WorldChange model, we offer the following key conclusions for ISM modelers. These apply to the class of difficult large-scale social problems like sustainability, which includes climate change:

1. *Solving problems in this class requires problem decomposition and root cause analysis, due to extreme system complexity.* This is our foundational conclusion. All other conclusions follow from it.
2. ISMs must therefore contain the explicit root causes of the problem they are modeling, in order to develop solution policies that have a high probability of success.
3. Reliably and efficiently finding root causes requires a process similar to the one in Figure 1. In particular, the process must produce models with explicit subproblems and their root causes. This is because of the strong assumption that if a model can endogenously reproduce reference mode behavior according to its dynamic hypothesis, then it must contain the "causes" of the problem. However, as demonstrated with three problem examples and the WorldChange model, this assumption does not hold in many important cases.

4. How to overcome systemic change resistance is the most important subproblem. The sustainability problem must therefore be decomposed into at least the original problem and how to overcome change resistance.
5. The simplest and fastest way to get started with the first four conclusions is to add a change resistance layer to existing ISMs.
6. Once systemic change resistance is overcome, solutions that are impossible in today's world become realistically possible, as discussed in scenarios 8 to 11.

These conclusions can be summarized: Adding a change resistance layer to ISMs that addresses the root causes of systemic change resistance has the potential to immediately transform the environmental sustainability problem from insolvable to solvable.

Beginning with World2 and World3, system dynamics models have been extremely helpful in bringing the environmental sustainability problem to the world's attention, providing detailed proof of the severity of the problem, and providing the range of forecasts needed for goal setting. With incorporation of the above conclusions, our models can be even more helpful and lead the way to *achieving* those goals.

Acknowledgements

(To be written later.)

Additional information2

The RCA-based process presented here is a simplified version of a larger one. For full description of the process, an analysis of the sustainability problem using the process, the study, and twelve sample solution elements, please see the book *Cutting Through Complexity: The Engineer's Guide to Solving Difficult Social Problems with Root Cause Analysis*, available at Thwink.org.

The WorldChange model may be found in the online version of this article at the publisher's website.

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