CGIAR Research Program on
Climate Change, Agriculture and Food Security (CCAFS)

Extended System Dynamics modelling of the impacts of food system drivers on food security, livelihoods and the environment

21 December 2010

Robert Muetzelfeldt

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Abstract

Food security research programmes, such as Global Environmental Change and Food Systems (GECAFS) and the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), need to consider extremely complex systems, with many agricultural, environmental, social and economic subsystems interacting with each other on a variety of scales and at a variety of levels on each. This poses considerable challenges in terms of representing the current state of knowledge, exploring how these systems might evolve in the future in response to external drivers and human input, and displaying the behaviour of the many variables involved in a way which is meaningful for stakeholders and policy advisers.

This paper aims to explore how a modelling approach based on System Dynamics can be used to:

- Represent influences and other relationships between the main agricultural and food system drivers and their consequences (i.e. outcomes) for the three areas of interest to CCAFS: food security, environment and livelihoods;
- Quantify these influences and outcomes as far as possible over time; and if these cannot be simulated directly, show how outputs from other models and tools could be incorporated;
- Represent dynamically the quantified outcomes on spider diagrams for CCAFS regional scenarios.
- Indicate how policy and technical interventions can be 'applied' to the system so as to show impacts in terms of changes to the spider diagrams.

The approach will be demonstrated using Simile, a visual modelling software developed specifically to meet the needs of ecosystem modelling. Simile supports System Dynamics modelling, like a number of other modelling packages (e.g. Stella, Vensim and Powersim), but has a number of additional capabilities which make it particularly suitable, including the ability to model object-based and disaggregated systems.

The heart of the paper is a consideration of how two forms of analysis used within food security programmes can be re-cast in Simile. The first is the Food Systems framework developed in GECAFS, an informal conceptual framework setting out the main constituents of food system *Activities*, and food security *Outcomes* and their interactions. I show that the framework diagram can be re-cast in Simile, giving both more formality (and thus standardisation) to the diagram itself, and the potential to develop runnable simulation models by fleshing out the diagram with values and relationships which apply in specific situations. The second is qualitative Scenario Analysis, used in both GECAFS and CCAFS for exploring possible futures under different scenarios. I show that the logical chains developed in such studies can be used to develop a single Simile model, which can then be used to investigate the different scenarios simply by changing the values for certain drivers.

The paper also considers how the values of multiple indicator variables can be displayed in a useful manner, concentrating on the spider diagram (one spoke per indicator, with a -- to ++ range for each variable). I show a spider diagram plugin for Simile which can be used to display static indicators, indicators which change in direct response to user input, or dynamically-changing indicators.

The paper concludes with the proposition that an approach based on extended System Dynamics has the potential to represent complex systems interactions in a formal standardised way; and that such representations can also form the basis for computable qualitative or quantitative models. It therefore supports a methodology which allows informal conceptual thinking by stakeholders and domain experts to be transformed smoothly into quantitative predictive models.

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The author is a director, shareholder and occasional employee of Simulistics Ltd, the company which develops and markets the Simile modelling software used in this paper.

1. Introduction

Food security research programmes, such as Global Environmental Change and Food Systems (GECAFS) and the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), need to consider extremely complex systems, with many agricultural, environmental, social and economic subsystems interacting with each other at on a variety of scales and at a variety of levels on each. This poses considerable challenges in terms of representing the current state of knowledge, exploring how these systems might evolve in the future in response to external drivers and human input, and displaying the behaviour of the many variables involved in a way which is meaningful for stakeholders and decision-makers.

This paper aims to explore how a modelling approach based on System Dynamics can be used to:

- Represent influences and other relationships between main agricultural and food system drivers and their consequences (i.e. outcomes) for the three areas of interest to CCAFS: food security, environment and livelihoods;
- Quantify these influences and outcomes as far as possible over time; and if these cannot be simulated directly, show how outputs from other models and tools could be incorporated;
- Represent dynamically the quantified outcomes on spider diagrams for CCAFS regional scenarios.
- Indicate how policy and technical interventions can be 'applied' to the system so as to show impacts in terms of changes to the spider diagrams.

To achieve these aims, I will be drawing on, and hoping to integrate, material from two separate sources. The first are various diagrams, tables and prose used in the food security arena, including scenario analyses. The second is a modelling approach called System Dynamics, extended to handle hierarchically-organised objects, as implemented in the Simile [URL in References section] modelling environment.

The paper is organised as follows. I will first summarise the main characteristics of Simile, a modelling environment developed specifically for ecosystem modelling. Simile was designed to integrate two major modelling paradigms - System Dynamics (stock-and-flow) modelling, and object-based modelling - within an intuitive, diagramming-based interface. It therefore provides a common environment for addressing the main goals of this study. Finally, I look back on what has been covered, and set out some proposals for realising these ideas within CCAFS.

2. Extended System Dynamics modelling with Simile

A number of modelling approaches have been used for analysing food security systems, including multi-agent systems (Barnard et al, 2008), Bayesian models () and System Dynamics (see Giraldo et al, 2008, for a review of a number of such models developed for modelling food security). System Dynamics is a particularly suitable approach, because it is based on concepts (influence and flow) which occur commonly in describing food security systems, even by people with no awareness of modelling. It therefore offers the possibility of a smooth progression from informal statements about such systems through to quantitative models.

A number of software packages have been developed to allow System Dynamics models to be constructed diagrammatically (by drawing stock-and-flow diagrams), and then attaching quantitative information - values and equations - to the model variables in order to define a mathematical model. These include Stella, Vensim and Powersim (URLs in Reference section], all of which have been used in various projects to model food security problems.

Simile (Muetzelfeldt and Massheder, 2003) is another System Dynamics-based visual modelling environment, originally developed in the Institute of Ecology and Resource Management at the University of Edinburgh, in the DfID-funded Agroforesty Modelling Project. Subsequent development took place within the DfID-funded FLORES project (Forest Land-Oriented Resource Envisioning System), and EU-funded project for modelling Mediterranean vegetation dynamics. In 2002 a University startup company, Simulistics Ltd), was formed to continue Simile development and to market the software and services built around it, in order to ensure the continued improvement and availability of the software.

Disclosure: I am a Director, shareholder and occasional employee of Simulistics.

Simile can be thought of as a standard System Dynamics modelling environment, in the same family as those considered above, but with one very important extension: the ability to handle complex disaggregated systems. This reflects Simile's origins in agroforestry modelling, since that context requires the ability to represent multiple objects (e.g. individual trees, hedgerows) and spatial aspects (e.g. spatial variations in soil water, vertical distribution of root density). This extension makes a huge difference, both to the range of models that can be built in Simile, but also to the intuitive concepts that can be used to build models.

I will first focus on Simile's capabilities for standard System Dynamics modelling. This discussion, and subsequent consideration of the relevance of standard System Dynamics for modelling food systems, could equally well have been illustrated with any of the commonly-available System Dynamics modelling software. Following that, I will consider Simile's capabilities for handling disaggregation, object-oriented modelling, and multi-agent systems. That discussion, and subsequent consideration of its relevance to modelling food systems, will be in terms that are unique to Simile.

2.1 Standard System Dynamics modelling in Simile

Fig. 1 shows a simple crop growth model represented in Simile.

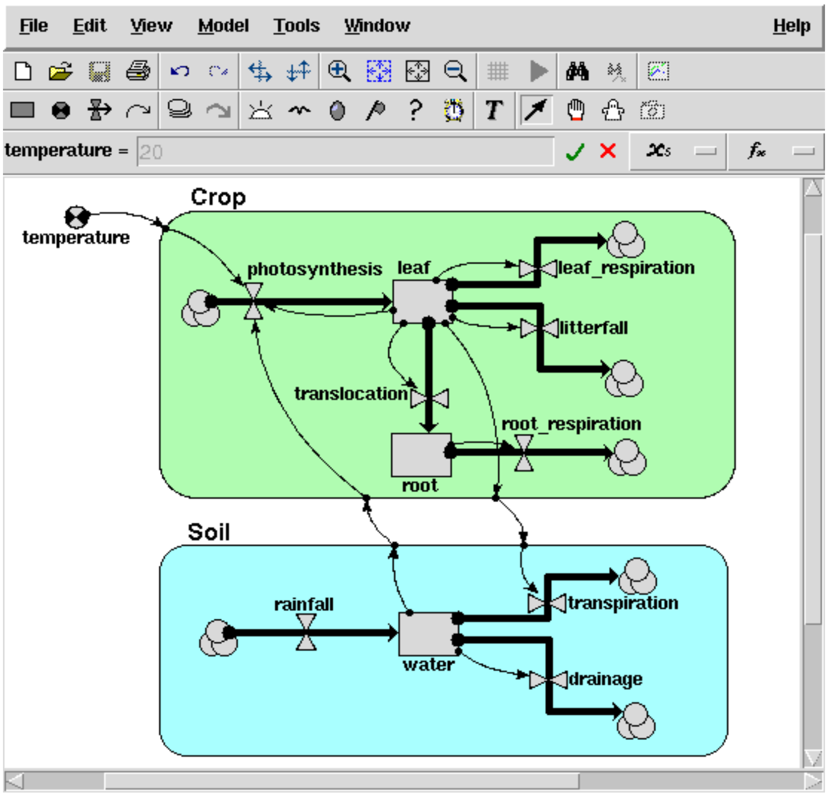

Fig. 1. A simple crop and soil water model in Simile. This screenshot shows the complete Simile model-design window, with the symbols used to construct the model shown on the 3rd line (immediately above the text 'temperature =').

The model has two submodels: Crop and Soil. In this model, the submodels are used purely for visual purposes, to show the main components of the model - they have no other significance.

The Crop submodel represents the storage (stock) of biomass in the crop, and the processes which increase and decrease the stored biomass.

There are two biomass stocks: leaf and root. Each one is represented by a Simile compartment - the rectangle symbol. Biomass flows into the leaf stock through photosynthesis, and is lost by metabolic respiration, leaf fall and translocation to the biomass stock in the roots. The root stock of biomass is increased by the translocation from the leaf, and lost by metabolic respiration. Each of these processes is conceptually a flow of material, and is represented by a flow arrow.

The Soil submodel has a single stock - the amount of water in the soil. There are 3 flows: rainfall into it, and transpiration and drainage out of it.

This stock-and-flow notation is very familiar and intuitive. As a first approximation, you can think of a stock as a tank that can hold some material, and the flows arrows are like pipes which allow the material to flow into, out of and between tanks[1]. We have seen such diagrams going back to our school days: diagrams showing the

1 This is a simplified view of what stocks and flows actually represent. Mathematically, a stock is a state variable, whose derivative (rate of change) is the sum of all the inflows minus all the outflows. Real-world stocks usually have an upper limit, and cannot go negative; whereas stocks in System Dynamics (at least in Simile) can potentially

hydrological, carbon or nitrogen cycle are basically just the same type of diagram.

A System Dynamics diagram also contains thin 'influence' arrows. These often relate pretty closely to our intuitive understanding of the word 'influence' (as in "income influences ability to buy food", and similar words such as "affects", "causes", etc. There are good examples in the sample model: temperature influences photosynthesis; and leaf biomass influences the loss of water by transpiration.

In order to be able to run the model, it is necessary to provide a value for those variables which are not influenced by any other, and an equation for those that are. Some equations are very simple - e.g. one that adds up the values of two variables - while others are more complicated and based on an underlying theory - e.g. the Penman-Monteith formula for evapotranspiration. When all variables have been quantified, the model can be run. Fig. 2. gives an example of the run-time interface: in this case, a graph showing the amount of leaf biomass and soil water (arbitrary units).

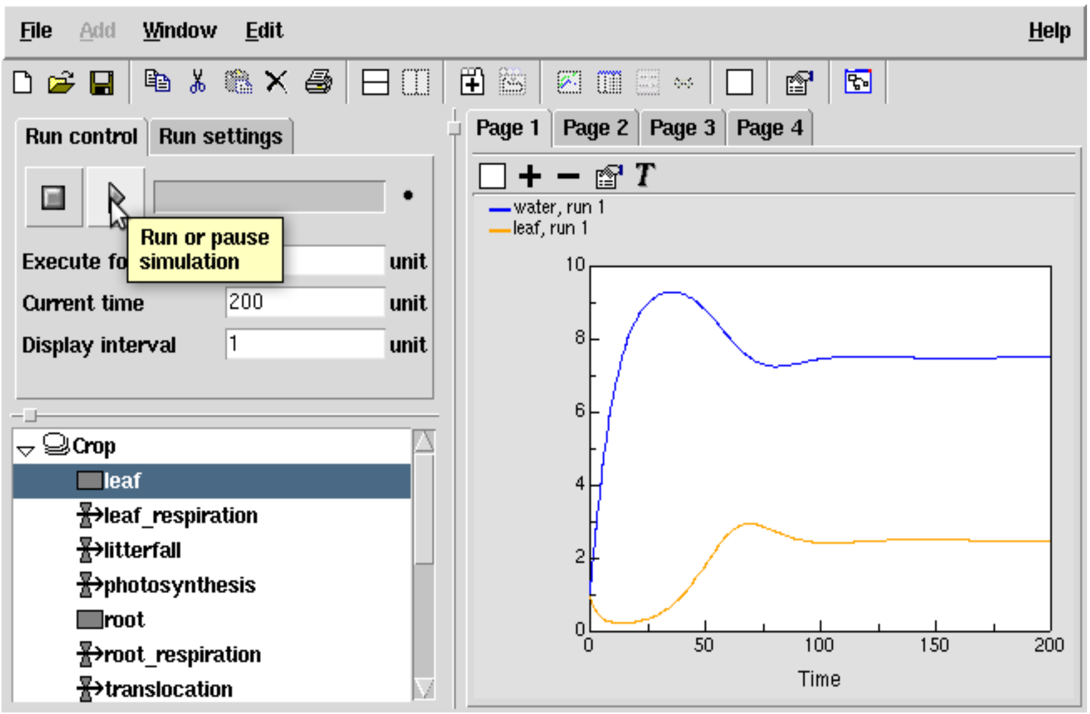

Fig. 2. The Simile run-time interface, showing a graph for soil water and leaf biomass.

2.2 Objects

As well as the concepts of influence and flow, another familiar concept is that of objects: for example, people (as individuals), or fields. We talk about a fixed number of objects (e.g. fields); r the number may change over time (people). Additionally, we often talk in terms of relationships between objects: a person <u>owns</u> a field; one field <u>is next to</u> another. Objects can have attributes (e.g. size) and behaviours (e.g. growth), and each separate object can have a different value for each attribute. By giving a collection of objects attributes defining x,y coordinates, we can easily define a spatial system: each object representing a grid square or a polygon, for example.

Simile has a simple but expressive notation for representing objects, and the relationships between them, in a model. A simple (and slightly simplified) example is shown in Fig. 3.

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have virtually infinite capacity and can go negative - it is up to the modeller to engineer things to simulate finite capacity and non-negative behaviour if that is what is required.

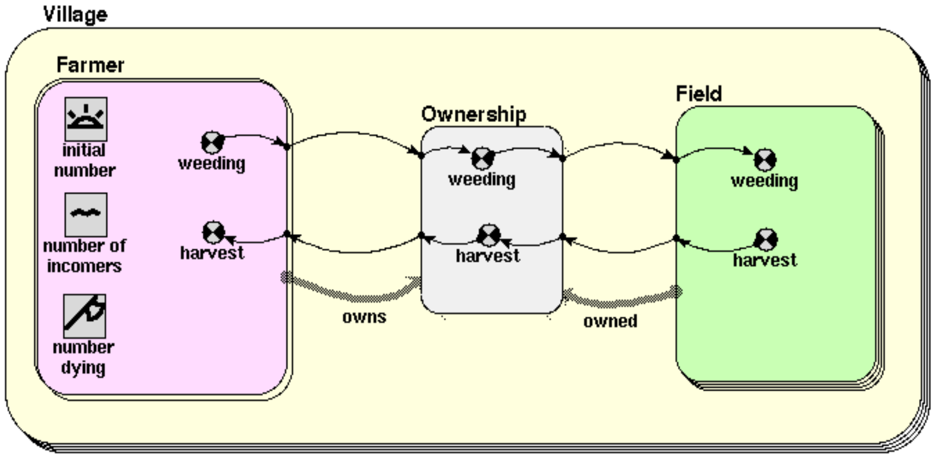

Fig. 3. An object-based model in Simile.

This model represents 3 types of object: village, farmer and field. Each of these is represented by a submodel. We can see that, unlike the previous example, the submodel boundaries indicate that there are multiple instances of each. For villages and fields, there is a fixed number of each. For farmers, the number can vary during the course of the simulation - it's a population. The three symbols on the left of the farmer submodel specify population characteristics: the initial number of farmers, the number of incomers per year, and the number dying per year.

The Ownership submodel captures the natural-language concept that "farmers own fields" (i.e. some fields are owned by some farmers). As well as having a descriptive role, in showing how various objects relate to each other, this submodel has a computational role, in that it allows information to flow between the two objects. In this case, the value for the amount of time spent weeding by each farmer is passed to the fields the farmer owns (e.g. to reduce the weed population); while the value for the harvest from each field is passed to the farmer who owns those fields.

Simile's capability for handling objects in this way is what sets it apart from other System Dynamics software, and represents a considerable extension to its capabilities. This capability makes it possible to describe and model spatial, hierarchical and agent-based aspects of Food Security systems, aspects which will become of increasing importance as the analysis of such systems becomes more sophisticated.

2.4 Relevant applications of Simile

Simile has been used for re-implementing a number of standard crop models, such as SUCROS and the AFRCwheat2 model. It has also been used to develop FLORES, a model of sustainable livelihoods at the forest margin (Prabhu et al, 2003; Haggith et al, 2003). This model includes considerable complexity, including spatial aspects, a dynamically-varying population of households, and complex socio-economic aspects such as tenure and short-and long-term decision-making. Simile was the modelling platform chosen for the MIMES (Multi-Scale Integrated Modelling of Ecosystem Services project, and was used in the HKKK Partnership project for modelling sustainable livelihoods in Nepal (URL in References section).

3. Re-casting the GECAFS Food Systems framework in Simile

The Food Systems framework has been developed during the GECAFS programme, and provides an overarching framework for the organisation of information gathered within particular food security studies. This framework is primarily intended for representing the main characteristics of particular food systems. Fig. 4 and 5. show the main components of this framework (from Ericksen, 2009).

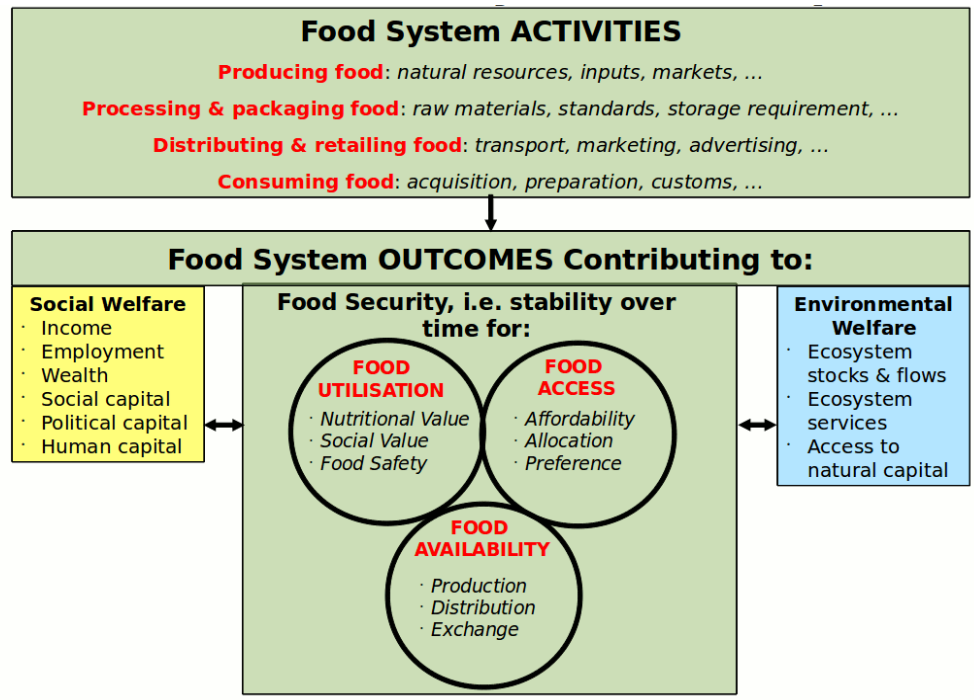

Fig. 4. The main Food System Concept diagram (from Ericksen, 2009).

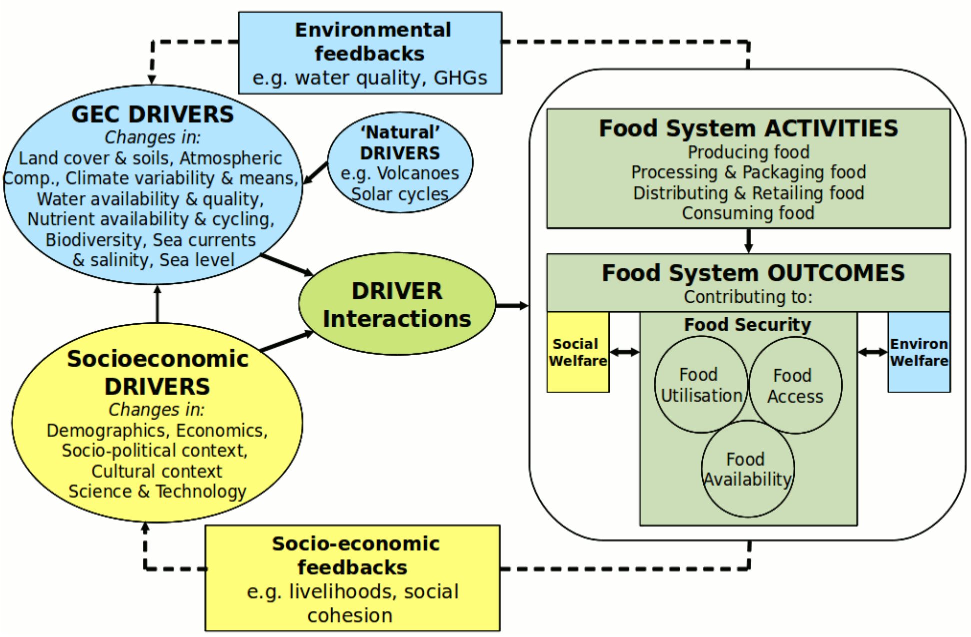

Fig. 5. The Food System concept diagram, with the addition of drivers and feedbacks (from Ericksen, 2009).

Fig. 6 shows one way in which the two food security framework diagrams above (Figs. 4 and 5) can be re-cast in Simile, capturing all the terms in the two original diagrams, and retaining the same colour coding. The following principles were used in the process:

- All symbols in the original diagram, regardless of their shape, are represented by Simile submodels.
- All terms inside shapes are represented as Simile variables, provided that they could reasonably be thought of as a variable (i.e. a quantity that has a value).
- All remaining terms are represented as internal submodels, implying that, when the framework is fleshed out with details for a particular locality, then variables would be added inside the submodel. For example, 'Ecosystem stocks and flows' is clearly not a variable, but we can readily envisage relevant variables in a specific context.

Three influence arrows have been added to the diagram, to illustrate how one might start to connect up variables in the different sections.

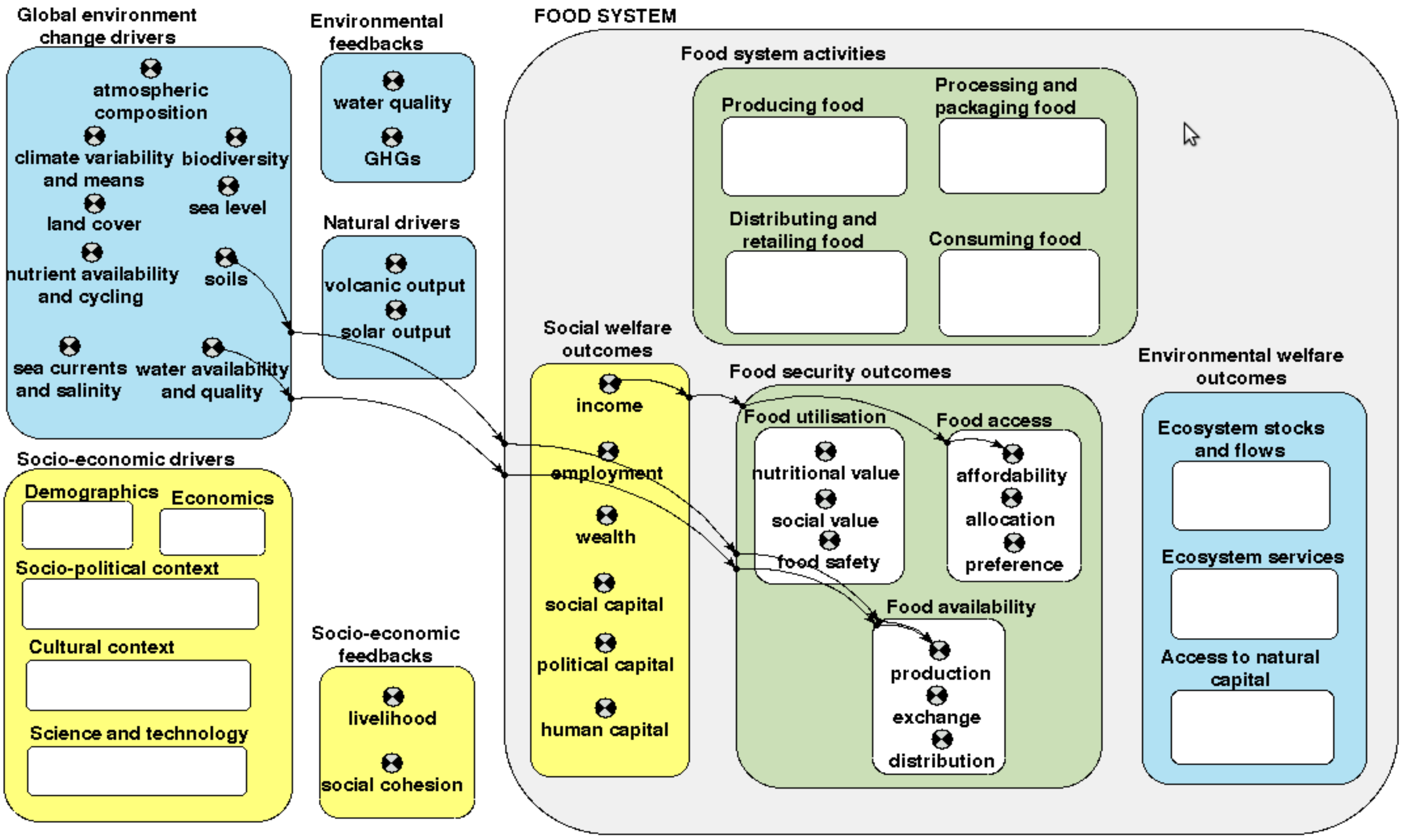

Fig. 6. Combined Food Systems framework diagram in Simile.

This exercise shows that the original informal diagram can be re-cast in Simile's formal notation with little loss of fidelity. The submodels provide a natural grouping mechanism. Simile variables are an appropriate way of capturing the "elements", "determinants" and "drivers" of the original diagram. And the influence arrow is an appropriate way of capturing the connections and feedbacks which can be identified in such systems - not just a graphical notation, but one with the same underlying semantics.

One can readily see how the framework diagram could be used as a basis for characterising individual case studies - for example, by removing submodels or variables which were not relevant in that context, or by replacing a generic variable (e.g. 'livelihood') with more specific terms appropriate to a specific context - e.g. 'fishermen livelihood' and 'farmer livelihood'. An example of this is given in Appendix A2.1, which shows how to take a causal chain from one such study and re-cast it in System Dynamic terms.

Having captured the food security framework in Simile, we can now ask whether it is useful to extend it using additional constructs, both in order to extend its descriptive power, and to provide the basis for a runnable simulation model. There are two main ways we can do this:

- by adding in a stock-and-flow notation;
- by defining sets of objects.

Adding in stocks and flows

So far, we have followed the principle that "everything that could have a value in the original framework becomes a Simile variable". And that principle has worked pretty well so far. However, some of the variables we would identify as we flesh out the framework for a specific context would be amounts of substance - stocks - and some would be rates of processes - flows. The appropriateness of this is already pretty evident - calling a submodel 'Ecosystem stocks and flows' is a bit of a give-away! - but we can infer that a stock-and-flow notation is probably desirable in other places as well. For example, 'wealth' and the various capitals are stock-like quantities - they change by processes which increase or decrease them, not by direct calculation from other quantities - and 'income', with its units of money/time, is probably best modelled as a flow. Fleshing out the 'Food system activities' submodel would probably lead to a consideration of the amount of food in different parts of the food chain and the flows between them, so again a stock-and-flow notation would be appropriate.

Handling multiplicity and scaling aspects

The current diagram is essentially flat, and the submodels have a purely cosmetic/visual function for grouping variables into cognate groups. However, descriptions of food systems frequently involve concepts of multiplicity and of scale, so we should consider how these can be incorporated. These two concepts are linked, but I will consider them separately.

Multiplicity can be relevant in a number of places in this framework: I will consider two. First, we will frequently want to deal with multiple types of food - particularly in the 'Food system activities' section. One way of handling this is to simply add in separate stocks, flows and variables for each food type. However, many food stuffs can be modelled in similar ways, differing only in amounts and rates. This allows us to use a single multiple-instance submodel, called perhaps 'Food type', greatly simplifying the model diagram and also indicating visually that the food-processing pathways for different foods are indeed similar.

Second, we may want to deal with multiple objects - say, villages. Rather than having one village, we may want to model a set of villages, perhaps because we are interested in variation between villages resulting from differences in social capital; or perhaps we believe that the interactions <u>between</u> villages (or regions, or whatever) is crucial to our understanding of food security in the area. To do this, we would need to make a submodel (called, say, 'Village') which encompassed all village-level aspects of the model, and to enclose that with a submodel representing the higher level on the spatial scale. Again, as we are finding repeatedly with Simile, this has both a visual-readability aspect - knowing Simile's language, we can now 'read' the diagram to see how scaling is handled - and a computational aspect.

Issues of scale arise when we want to model a system which includes processes at the village level <u>and</u> at the region level and at the national level. As Ingram has pointed out (Ingram 2009), this is an intrinsic aspect of many food security systems. Simile provides a simple way of capturing this, simply by embedding a Village submodel inside a Region one, and a Region submodel inside a National one. See Appendix 2.3 for more detail.

4. Scenario Analysis

Scenario analysis is process for exploring possible futures under a range of different conditions (scenarios). Scenario analyses fall broadly into one of two main types: quantitative and qualitative.

Quantitative scenario analyses use a single mathematical model. A set of inputs are grouped together, and different scenarios are represented by different values for this set of inputs. For each set, the model is run, and the results are used to indicate the behaviour of the system for that particular scenario. This approach is widely used in certain communities (particularly industry), and there are a number of software tools which support it - e.g. Podium [URL in References section]. Indeed, Microsoft Excel has a plugin which directly implements this approach.

Implementing such an approach in Simile is straightforward. Simile allows the modeller to create a set of alternative data input files (SPFs, or "Simile Parameter Files") for a given model. Each file could correspond to a different scenario, so switching between scenarios is simply a matter of switching between alternative SPFs.

However, the approach used in the GECAFS/CCAFS programmes is qualitative scenario analysis, which largely depends on verbal statements and expert opinion to draw conclusions about possible futures under different conditions. This presents considerable challenges for a Simile-based approach. Since my goal throughout this paper has been to take existing modes of thinking within food security as my starting point, we need to explore how, or if, Simile has anything to offer in this area.

From now on, I will use the term 'scenario analysis' to mean 'qualitative scenario analysis',

In this section, I will draw on information taken from the Interim Report on CCAFS Regional Scenarios Development for East Africa (CCAFS Scenarios Team, 2010). This presents results from the most recent CCAFS workshop on scenario analysis for food security, and contains information on 13 variables that contribute to food security, environmental and livelihood outcomes (Box 1) for each of 4 scenarios.

1.Variables that contribute to Food security outcomes
- affordability of staple foods
- regional production of staple foods
- effectiveness of distribution mechanisms
- nutritional value of staple foods

2.Variables that contribute to Environmental outcomes
- water quality
- soil quality
- forest cover
- biodiversity status
- water sufficiency for agriculture

3.Variables that contribute to Social/livelihood outcomes
- financial wealth of individuals (includes income and assets)
- social capital at community level
- health
- knowledge and skills necessary to ensure that the whole food system operates efficiently and innovatively

Box 1: Thirteen FSEL variables that contribute to food security, environmental and livelihood outcomes.

I will first present direct extracts from this report, showing clearly how 3 possible outcomes for one scenario were derived, then I will re-cast the informally-expressed logic from this report in Simile terms. The aim is to demonstrate that, even when an analysis was undertaken without the specific intention of expressing it in System Dynamics terms, it is still possible to do this without significant loss of fidelity. In other words, ***conventional scenario analysis can be a valid starting point for the construction of a System Dynamics model.***

The report includes 4 tables, one for each scenario (the four combinations of regional integration/status quo and proactive/reactive governments). Each table has 13 boxes, one for each of the 13 "FSEL outcomes" - i.e. the Food Security, Environment and Livelihoods outcome indicators. The FSEL outcomes are grouped into 3 groups: food security, environment and social/livelihood.

I have taken one outcome from each of the 3 groups for one scenario: regional integration + proactive. This is therefore just 3 out of the 4x13 = 52 analyses, but this should be sufficient to demonstrate the principles used and to demonstrate the feasibility of the approach. Table 1 presents the actual text used in the original report for these 3 cases.

FSEL group	**FSEL variable**	**Description of change**	**Net effect (2030)**
Food security outcomes	Affordability	Greater employment opportunities resulting from free movement of labour and increased economic growth of the region lead to increased incomes. **(+)** Increased productivity of both crop and livestock farming and better export market prices lead to increased income for farmers from crops and livestock, but more expensive food for consumers. **(-)** Local food prices increase, but governments ensure regional breadbaskets continue to produce basic staple crops for sale at affordable prices. **(+)**	+
E**nvironment outcomes**	Forest cover	Proactive afforestation helps to reverse forest cover depletion. **(++)**	++
Social/livelihoods outcomes	Health	Strong regional and national governance structures provide for and facilitate access to better health services that lead to a healthier workforce in the agriculture sector. **(+)**	+

FSEL group	FSEL variable	Description of change	Net effect (2030)
		Regional health programs on HIV/AIDS, malaria, etc. lead to lower mortalities and increased agricultural workforce **(+)**. In spite of massive donor funding, campaigns mounted in the EAC region against the spread of malaria to new areas due to warmer temperatures prove to be ineffective. **(-)**	

Table 1. Extract from the "Analysis of FSEL variables" table in CCAFS Scenarios Team (2010).

Fig. 7 shows one possible way in which the information in the above table can be re-cast in Simile. In doing this, I have tried to be as complete and as faithful to the original text as possible, without getting too silly about it.

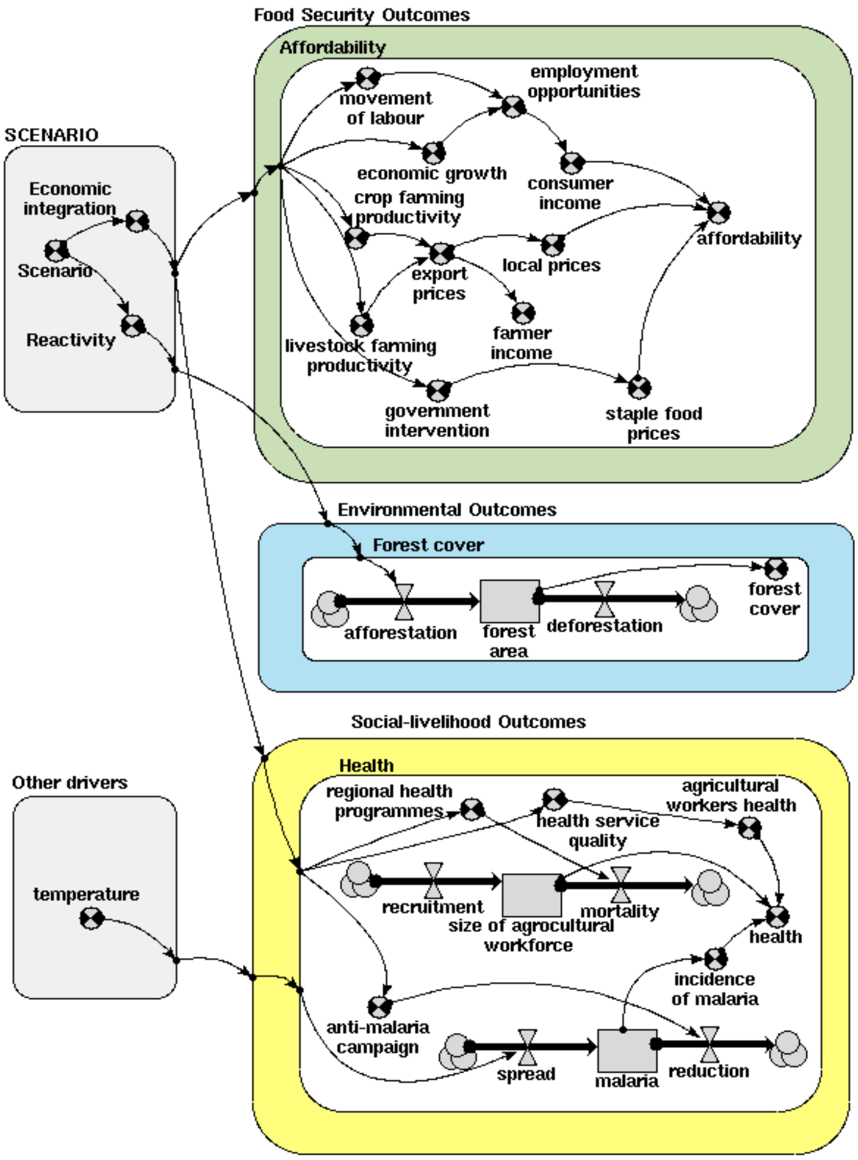

Fig. 7. Re-casting of the information in Table 1 using Simile symbols

The idea behind this exercise is that there needs to be only <u>one</u> model to cater for all 4 scenarios. (This contrasts with the original information, which had a separate table for each scenario.) The model has an input variable - Scenario - which can be set to one of the 4 values 1, 2, 3 or 4. This is then used to derive a value for Economic integration and for Reactivity. Simile allows variables to have text values (to be precise, enumerated types), so the two possible values for Economic integration are "regional_integration" and "status_quo", and for Reactivity are "proactive" and "reactive".

The 3 submodels on the right of the diagram correspond to the 3 FSEL groups. Each one contains a single submodel - one FSEL variable. If this exercise were completed, then the groups would contain 4, 5 and 4 submodels respectively, that being the number of FSEL variables in each group. On the right of the submodel for each FSEL variable is the variable itself, which should have an integer value between -2 and +2 (corresponding to --, -, 0, + and ++). Each FSEL variable is calculated from a set of supplementary variables, corresponding to the bracketed signs in the "Description of change" column in the original table.

In most cases, the variables which we need, as suggested by the original text, can be quite reasonably represented using Simile variables. In a couple of places, however, I have instead introduced stock-and-flow symbols. To see why, consider the case of forest cover. The original text says that "Proactive afforestation helps to reverse forest cover depletion", but the FSEL variable is forest cover. The latter is the amount of forest cover - let's say, in hectares. The former - forest cover depletion - is a process which reduces the amount, and has units such as hectares per year. Afforestation is a process which increases the amount of forest cover, and has the same units of hectares per year. All of this suggests that forest cover should be represented as a stock, with afforestation as an inflow influenced by the 'Reactivity' of the government, and that forest cover depletion as an outflow.

The question of how to represent a particular quantity in System Dynamics - as a variable, flow or stock - is a fraught one, which causes quite a lot of confusion for newbie modellers. In some cases, it is not obvious even for seasoned practitioners. My aim here is not to provide clear guidelines on how to do this, but to show that the process of re-casting the original scenario analysis text in System Dynamics terms <u>might</u> involve the introduction of stocks and flows. Whether it is actually the appropriate thing to do in particular situations needs careful consideration.

Formulating equations for a model such as this can vary from being very straightforward to pretty challenging. The fall-back position, especially when the model is closely related to a workshop-style scenario analysis exercise, is to formulate the equations as qualitative rules which correspond closely to those developed in the workshop process. For quantitative variables which have only one influence, the equation can often be expressed as an if...then rule, or represented as a sketched graph, either of which non-quantitative practitioners can work with readability after a little training. For quantitative variables which have multiple influences, then often there are simple ways of combining the variables - e.g. multiplying or adding them together. Which leaves the difficult cases, when a variable is influenced by multiple other variables, and there is no obvious way of combining them. There are guidelines and tricks which work well in many such situations, but the best thing is to consult a seasoned modeller for advice.

5. Displaying multi-indicator behaviours

The Terms of Reference for this paper require that I discuss "*How Simile and similar approaches (e.g. Stella) can help to ... represent dynamically the quantified outcomes on spider diagrams for CCAFS regional scenarios; and to indicate how policy and technical interventions can be 'applied' to the system so as to show impacts in terms of changes to the spider diagrams.*"

In preparing this section of the paper, I have rapidly prototyped a spider diagram display for Simile models. Simile is unusual, if not unique, in the family of System Dynamics modelling software in that it allows the user to develop their own display tools, totally independently of the Simile developers. These are written in a scripting language, and added to the relevant directory in one's own Simile installation. I have used this mechanism to implement a simple spider diagram display.

I use this display tool linked to Simile models to demonstrate 3 cases:

- the simple static display of values from a scenario analysis exercise;
- the display of values which directly respond to a set of input sliders (drivers);
- the display of values resulting from a dynamic model, with appearance of the spider diagram changing during the course of the simulation.

Fig. 8 shows an example of a spider diagram taken from the East African scenarios exercise (CCAFS Scenarios Team, 2010). In this study, there are 4 such diagrams, one for each scenario. The precise method used to determine the values for the indicators is not relevant here, but essentially each value (on a scale of --, -, 0, +, ++) was obtained by summing pluses and minuses for several sub-indicators (e.g. 0 plus ++ gives a +), and the value for each sub-indicator was assessed by the scenario team.

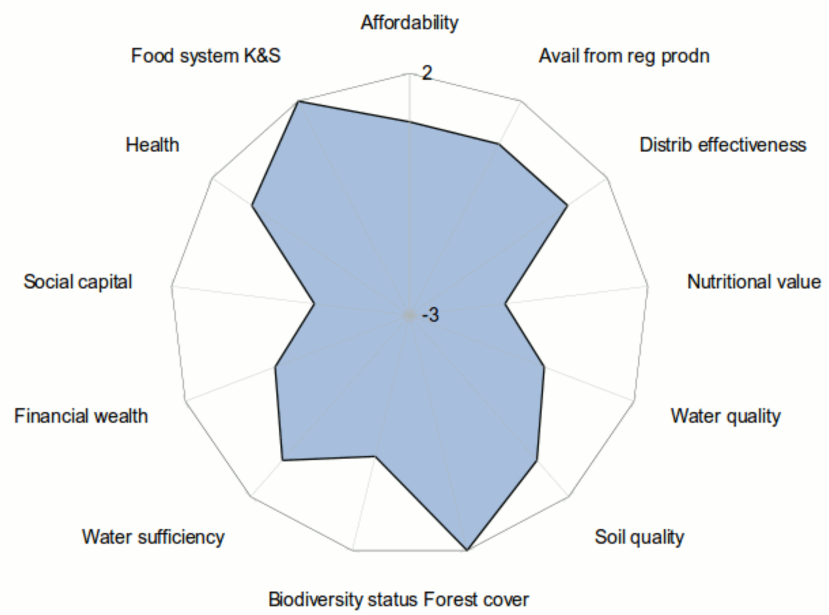

Fig. 8. Original spider diagram for East African scenario analysis exercise (as presented in the main report from the workshop). Scenario 1: Regional integration and pro-active

5.1 Static display of indicator values

The following figure (Fig. 9) is a trivial Simile "model" - actually, just a set of 13 variables which take their values from an external data file. There is one data file for each of the 4 scenarios, containing 13 values, one for each FSEL indicator. This provides a simple mechanism for picking up the 13 values.

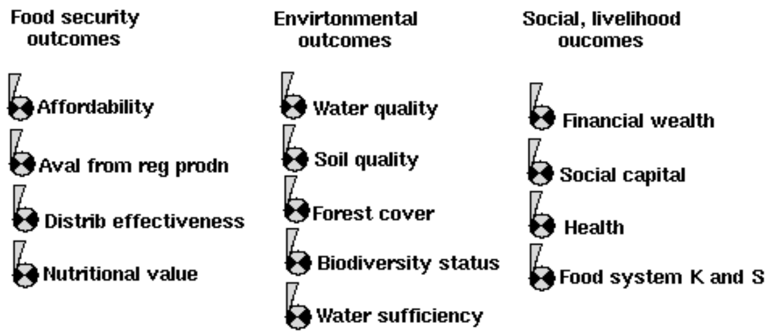

Fig. 9. Simile model diagram for a "model" whose only job is to hold a static set of values for indicators read in from an external data file.

Fig. 10 shows the Simile spider diagram when this model is loaded, and the data file accessed. You can see that it corresponds closely to the original. (The only slight difference is that the original was scaled from -3 to +2, whereas the Simile one is -2 to +2: this is trivial to change.)

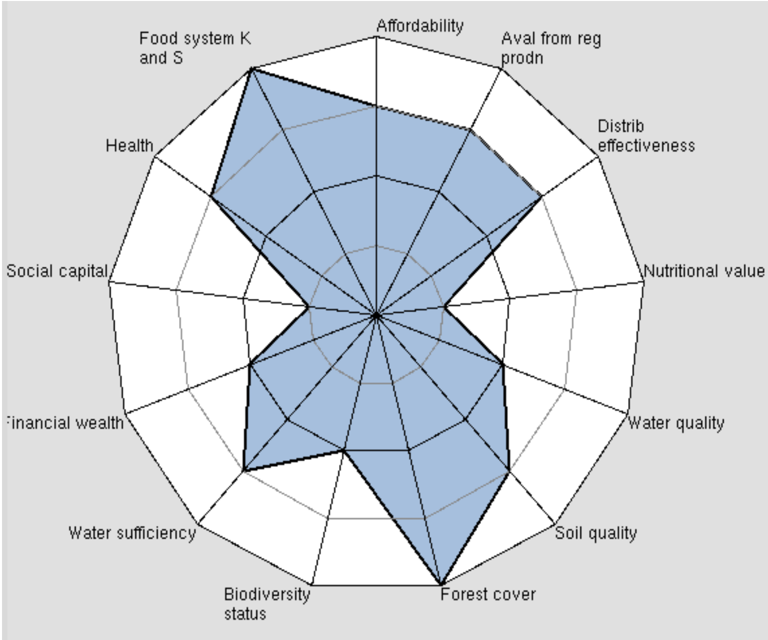

Fig. 10. Simile spider diagram display for the above model, with the 13 indicators having the same values for scenario 1, as presented in the East Africa scenario analysis report.

5.2 Display of values resulting directly from changes to drivers

From Scenario 1 (Regional integration and Proactive):

The impacts of one degree increase in temp will start to reduce regional food production by 5% by 2030. (-) Despite this, regional food production increased by 50% due to increased use of improved technologies, such as irrigation, fertilisers, improved crop varieties and livestock breeds. (+ +).

There are many ways of re-casting this logic in a System Dynamics model. For illustrative purposes, I have chosen to represent "one degree increase in temp" as a Boolean variable (true/false), 'temperature increase'. We can consider this to be a driver (in the sense of an input which is not affected by anything else in the model) which can be turned on or off. I have identified the two signed terms (regional food production and impact of technology on food production) with two Simile variables: 'Baseline production' and 'Production increase from technology' (Fig. 11)

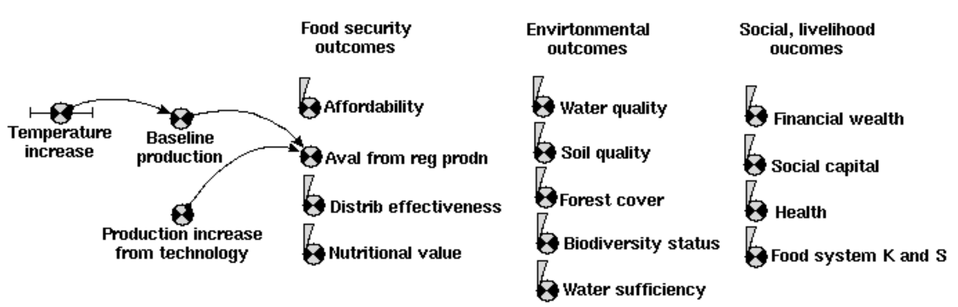

Fig. 11. Simile diagram for a model with one indicator (Aval from reg prodn) calculated from rules produced by workshop participants.

The resulting spider diagram is identical to Fig. 10 above when 'temperature increase' is set to 'true'. When 'temperature increase' is set to 'false', then 'Aval from reg prodn' arm goes up to maximum value of +2, as expected.

Temperature increase is, in Simile terms, a "variable parameter": its value can be set by the user at the start of a simulation by setting a check-box (for Boolean variables), or by moving a slider (for numeric variables). Simile automatically generates the check-boxes and sliders for all the 'variable parameters' in the model, thus providing a simple control panel for allowing the model user quickly to explore the behaviour of the model for different settings of its inputs (drivers).

5.3 Display of dynamically-changing indicator values

The real value of using Simile it comes from modelling dynamic change over the future, rather than simple influence relationships as above. We thus want our spider diagram to be able to visualise these changes during the course of the simulation.

Simile display tools can automatically show such dynamic change in the variables being displayed. In order to demonstrate this, the previous version of the East Africa scenarios model was modified to make one of the indicators - 'Aval from reg prodn' - a function of dynamically-changing variables. This could of course be a complex dynamic model, modelling factors such as a change in soil fertility, the impact of AIDS on the availability of farm labour, etc. However, since the only aim here is to demonstrate a dynamic spider diagram, this was kept as simple as possible.

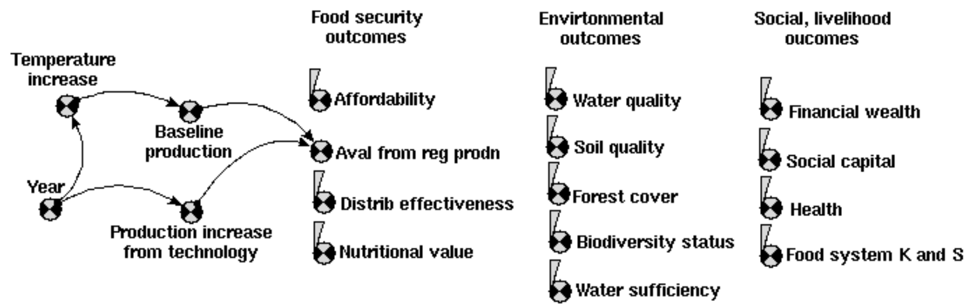

Fig. 12. Dynamically-changing regional production.

Fig. 12 shows a very simple model of dynamically-changing regional production, 'Aval from reg prodn'. It remains a simple sum of 'Baseline production' and 'Production increase from technology'. However, each of these is now a function of the year of the simulation.

When you run this model, the spider diagram is now animated - the point on the 'Aval from reg prodn' spoke moves up and down while the simulation is running, changing the shape of the spider diagram polygon in the process.

6. Conclusions

The conclusions of this study are expressed in relation to the original Terms of Reference.

How a modelling approach based on System Dynamics can be used to present influences and other relationships between main agricultural and food system drivers and their consequences (i.e. outcomes) for the three areas of interest to CCAFS: food security, environment and livelihoods.

The analysis of the CCAFS food security framework showed that this framework can be directly mapped on to a hierarchical submodel framework in Simile. Having done this, individual variables (drivers, outcomes) can be represented by Simile variables and stocks, and the relationships between them represented by Simile influence arrows.

The analysis of the East Africa scenario analysis showed that the informal statements used to score likely changes in various FSEL indicators can be re-expressed as System Dynamics influences, which in turn can be re-cast, where required, as System Dynamics stocks and flows.

Appendix 2 shows in more detail how the familiar concepts of influence, flow and object can be represented in Simile terms.

How a modelling approach based on System Dynamics can be used to quantify these influences and outcomes as far as possible over time; and if these cannot be simulated directly, show how outputs from other models and tools could be incorporated.

The Simile diagram, whether derived from the Food Security framework or from scenario analyses, can be developed into a quantified model by providing numeric values for drivers, and equations for the relationships between variables, using standard System Dynamics modelling techniques.

The output of models of particular subsystems can be included in one of three main ways. First, the output of these models (e.g. climate models) can be used to provide time-series data input into the model developed within the framework. Second, the behaviour of other models can be summarised in terms of a tabular or a response surface, and this can be included as tabulated functions in the Simile model. Third, Simile allows external programmed models (e.g. hydrological models) to be incorporated directly, as black box models.

Explore how a modelling approach based on System Dynamics can be used to:
- represent dynamically the quantified outcomes on spider diagrams for CCAFS regional scenarios.
- indicate how policy and technical interventions can be 'applied' to the system so as to show impacts in terms of changes to the spider diagrams.

The work reported in section 5 has demonstrated that it is straightforward to add a spider diagram display to Simile's repertoire of display tools. This can be used dynamically displaying the values of user-selected indicator variables during the course of the simulation, and for showing how indicator variables respond to variations in settings (policy and technical interventions) provided by the user.

7. Implementing a System Dynamics-based approach

The Terms of Reference request an estimate of the requirements for implementing the approach.

This paper has put forward two key ideas:

1. that extended System Dynamics provides a powerful notation for describing food security systems (qualitative models) (even if this does not lead to a quantitative model); and
2. that quantitative models can be developed by a smooth progression from qualitative ones.

It is my recommendation that, if these ideas are accepted, then their implementation is based on 3 principles:

1. the sustainability and autonomous uptake of the approach not only during but also after the end of CCAFS;
2. the eventual non-dependence on any one software product for extended System Dynamics modelling (i.e. eventual non-dependence on Simile); and
3. the shareability of both qualitative and quantitative models within the food security community.

The first principle expresses the idea that groups should be able to develop both qualitative and quantitative models without having to be guided by external advisers This requires the development of distance learning material plus the provision of software tools to enable groups to develop their own capabilities. The second principle is aimed at reducing concerns on the dependence on a single (and commercial) software product. This requires the development of a standard model interchange language for sharing both qualitative and quantitative models. (Simile already has such a language, but it was not developed as a community standard). The third principle recognises that both the qualitative and quantitative models represent valuable forms of knowledge, and therefore there is benefit in sharing them with others. This principle is satisfied automatically if there is such a standard model-interchange language.

If these principles are accepted, then it follows that a key focus of work within the lifetime of CCAFS should be on ensuring that the resources are developed and tested to support the above strategy. This can be achieved through the following investments:

1. Development work on Simile to increase its suitability for the development of qualitative and quantitative models, to facilitate its use for exploring policy and technical interventions, and for improving its display tools for multiple indicators (e.g. spider diagrams)

2. Expert input into the design of a methodology for building qualitative and quantitative models within the context of Scenario Analysis activities; and into ensuring the long-term uptake and sustainability of the approach.

3. Development of common standards, distance learning material and software tools to enable groups to adopt the approach autonomously and share models, using a mixture of in-house capability and external expertise.

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Simile: http://www.simulistics.com
Stella: http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx
Vensim: http://www.vensim.com

Appendix 1. Terms of Reference

1. To draft and deliver by 21 December 2010 to the CCAFS scenarios team in Oxford a 10-15 page background paper on how SIMILE and similar approaches (e.g. STELLA) can help to:

a. Identify influences and other relationships between main agricultural and food system drivers and their consequences (i.e. outcomes) for the three areas of interest to CCAFS: food security, environmental and livelihoods.

b. Quantify these influences and outcomes as far as possible over time; and if these cannot be simulated directly, show how outputs from other models and tools could be incorporated.

c. Represent dynamically the quantified outcomes on spider diagrams for CCAFS regional scenarios.

d. Indicate how policy and technical interventions can be 'applied' to the system so as to show impacts in terms of changes to the spider diagrams.

2. Indicate time requirements to implement these outputs.

3. Present and discuss the paper at the CCAFS Scenarios Advisory Group Meeting in Oxford on 20-21 January 2011.

Appendix 2. Translating influence, flow and object concepts into Simile

In Section 2 I demonstrated that Simile supports three types of conceptual thinking: influences, flows and objects. In this Appendix I will look at how these three concepts relate to those used in thinking about food systems.

A2.1 Causal/influence relationships

The concept of something affecting something else is a very common one in discussions of food systems. Very often it is simply expressed in natural language (text), and can be identified by looking for signal terms such as "affects", "causes", "influences", "because of", and so on. But it is also quite common to see diagrams which set out a network of such relationships in a way which is easier to absorb. I will consider in some detail how such forms of expression can be captured in Simile, using mainly (but not only) the Simile 'influence' arrow.

There is a subtle but important difference between causal statements and influence statements. "An increase in humidity causes an increase disease" is a causal statement, whereas "Humidity has a positive influence on disease" is an influence statement which (arguably) means the same thing. The first is expressed in terms of changes in variables; the second in terms of the variables themselves. Confusion in this area is increased by the fact that some "causal diagrams" actually show influences. There is not room to unravel the semantic issues involved here. I'll just say that all such relationships in Simile (and other System Dynamics software) are expressed as influences; and extracting such influence relationships from existing prose and diagrams requires some care and awareness of the differences in meaning.

Verbal statements of causal or influence relationships

Although I could choose from many examples of causal/influence statements in published documents, it would take up more space in this paper to present the original text, and following the re-casting into Simile would involve more work for you, the reader. I have therefore chosen an example which, while expressed in text, is already pretty concise.

The following text is taken verbatim from Sidhi and Vatta (2009):

Increasing Relative Humidity: Higher insect-pest attacks → increasing cost of production and falling income → Declining access [to food]

Note that these are causal statements, not influence statements: they are expressed in terms of the (change of) values of variables, rather than simply variables themselves. The following expresses the same information, but in the form of an influence chain:

Relative humidity **(+)**→ Insect-pest attacks **(+)**→ cost of production **(-)**→ income **(+)**→ access

where (+)→ indicates a positive influence, and (-)→ a negative one.

The following Simile diagram (Fig. 13) captures the influence chain. It does not, however, indicate the sign of the influence, though other System Dynamics software, such as Vensim, does.

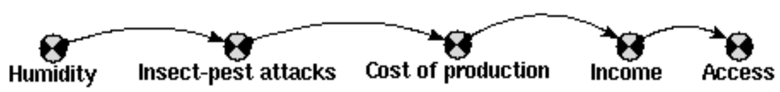

Fig. 13. A simple influence chain in Simile.

This has several advantages over the informal text form. First, it imposes a degree of formality, which reduces the scope for differing interpretations (see the colon and the 'and' in the original text, both of which I interpreted as 'causes'). Second, it opens up the possibility of combing this knowledge fragment with others, especially if the community can agree on a standard controlled vocabulary for terms such as 'income'. Third, it makes it possible to perform automatic reasoning with the influence chain - for example, appropriate software can readily answer the question: What are all the factors that affect 'Cost of production'?" or "What things are affected by 'insect-pest attacks'?". Finally, it makes it possible to perform quantitative predictions, if each relationship is expressed mathematically rather than as a simple positive or negative influence - so we could calculate the change in 'Access' for a given change in 'Humidity'.

Diagrammatic representations of networks of causal or influence relationships

Fig. 14 shows the relationships between livestock, crop production, capital and food security in a district in Ethiopia (Hawkins, 2009) It is a typical example of a signed influence diagram, and has an obvious and direct re-casting in Simile (Fig. 15)

Fig. 14. A signed influence diagram, showing the relationships between livestock, crop production, capital and food security in an Ethiopian district (Hawkins, 2009).

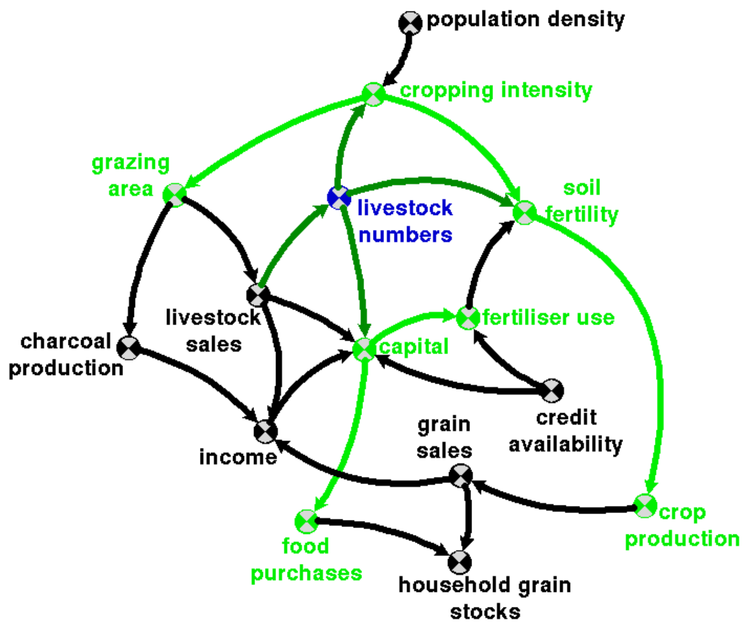

Fig. 15. Re-implementation of the signed influence diagram in Simile. Note that Simile allows automatic highlighting of variables which influence or which are influenced by a selected variable. In this case, the user has selected 'livestock numbers', and requested that <u>influenced</u> variables 1 or 2 links away be highlighted (light green).

There are several things to note about this example. First, Simile provides a tool which for drawing influence diagrams which is easy to use, has a direct correspondence with the original diagram, but imposes a degree of formality which is not necessarily present if the same diagram is drawn in (for example) Powerpoint. Second, Simile allows some (fairly primitive) processing to be performed on the influence network - in this case, highlighting all variables which are directly or indirectly influenced by a selected variable. Third, Simile stores models in an open text format (Prolog or XML): this enables anyone to process or combine such diagrams using software which is totally independent of Simile itself.

The final point relates to the relationship between description and quantitative modelling. The above Simile diagram is a fine visual representation of the original influence diagram. But, because it is in Simile, it is also potentially a quantitative model: we can give each variable a number or equation, and calculate the values for the variables for the given set of inputs. But is it a good model? Any System Dynamics modeller would look at terms such as 'livestock numbers', 'capital', and 'grazing area' - all of which represent an amount of something, which changes by addition or subtraction - and consider that (subject to some provisos) they would be better modelled as stocks, with appropriate flows. In other words, useful as it is to re-cast an influence model in Simile, we should not unthinkingly accept that as a valid quantitative model. Rather, we need to use it as a starting point for a proper modelling analysis of the system, and this requires expertise and experience.

A2.2 Flow diagrams

Food systems are, to a large extent, flow systems. Food itself flows from producer to storage to market to consumer. Money flows in the reverse direction. And cycles of nutrients, carbon, water and supplementary substances (like pesticides) are of fundamental importance for understanding how the food system functions.

One common form of flow diagram for food systems is the farm systems diagram. The following example (Fig. 16) is taken from a manual for farm-level aquaculture in the Philippines.

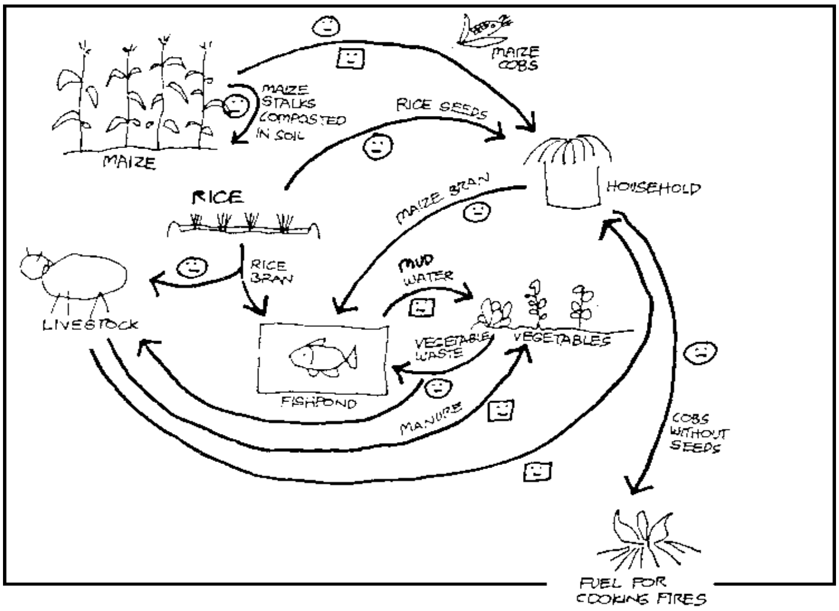

Fig. 16. A simple farm-scale flow diagram

The following Simile diagram (Fig. 17) shows how just one flow pathway - that relating to maize - could be represented as a System Dynamics flow diagram.

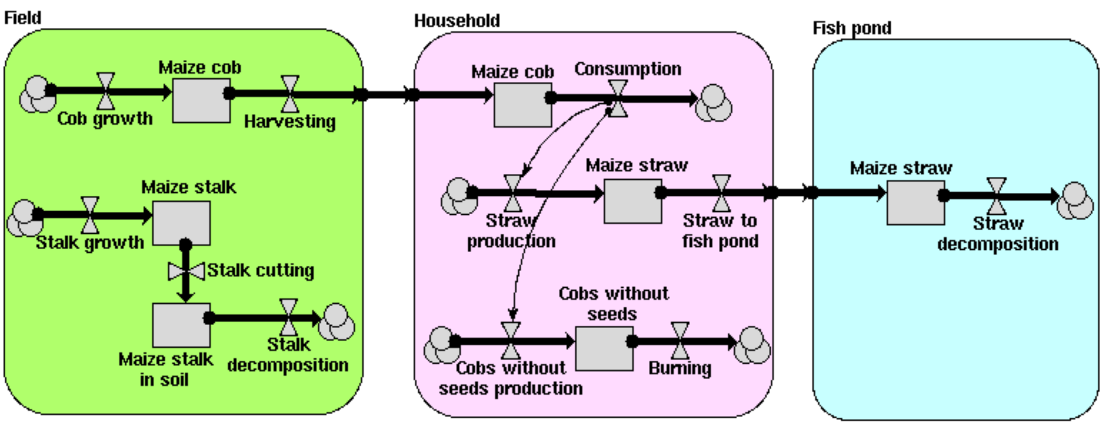

Fig. 17. Maize flow pathway in Simile

There are several things to note about this solution.

- We use Simile submodels to separate out the main components of the system (field, household and fish pond). Apart from being visually helpful, this allows us to use the same name (e..g., Maize cob) in different parts of the diagram.

- We identify the flows which correspond to those on the diagram with a suitable flow (process) name, rather than the material that is flowing along it.
- The material is associated with the stock (rather than with the flow).
- Stocks containing the same 'thing' (e.g. maize cob) can be connected by a flow, but...
- Stocks containing a different thing (e.g. cob vs. stalk) need to be represented by separate stocks. This is perhaps the most significant difference between conventional, informal flow diagrams and flow diagrams which conform to System Dynamics.
- Additional flows have been added (e.g. Cob growth) to ensure that all relevant processes are included.
- The diagram also includes two influence arrows - from Consumption to Straw production and Cobs without seeds production. This steps outside the pure stock-and-flow notation, but these two are included to show one possible way of handling the fact that individual cobs in fact consist of several substances. (An alternative would be to have three separate stocks in the Field submodel, one for the seed, one for the straw, and one for the central core.) If this were an actual complete model, rather than simply a flow diagram, there would potentially be a number of influences, showing the factors which determine the rates of the various flows.

The following is another example of a published flow diagram, showing stocks and flows within a food system at regional level.

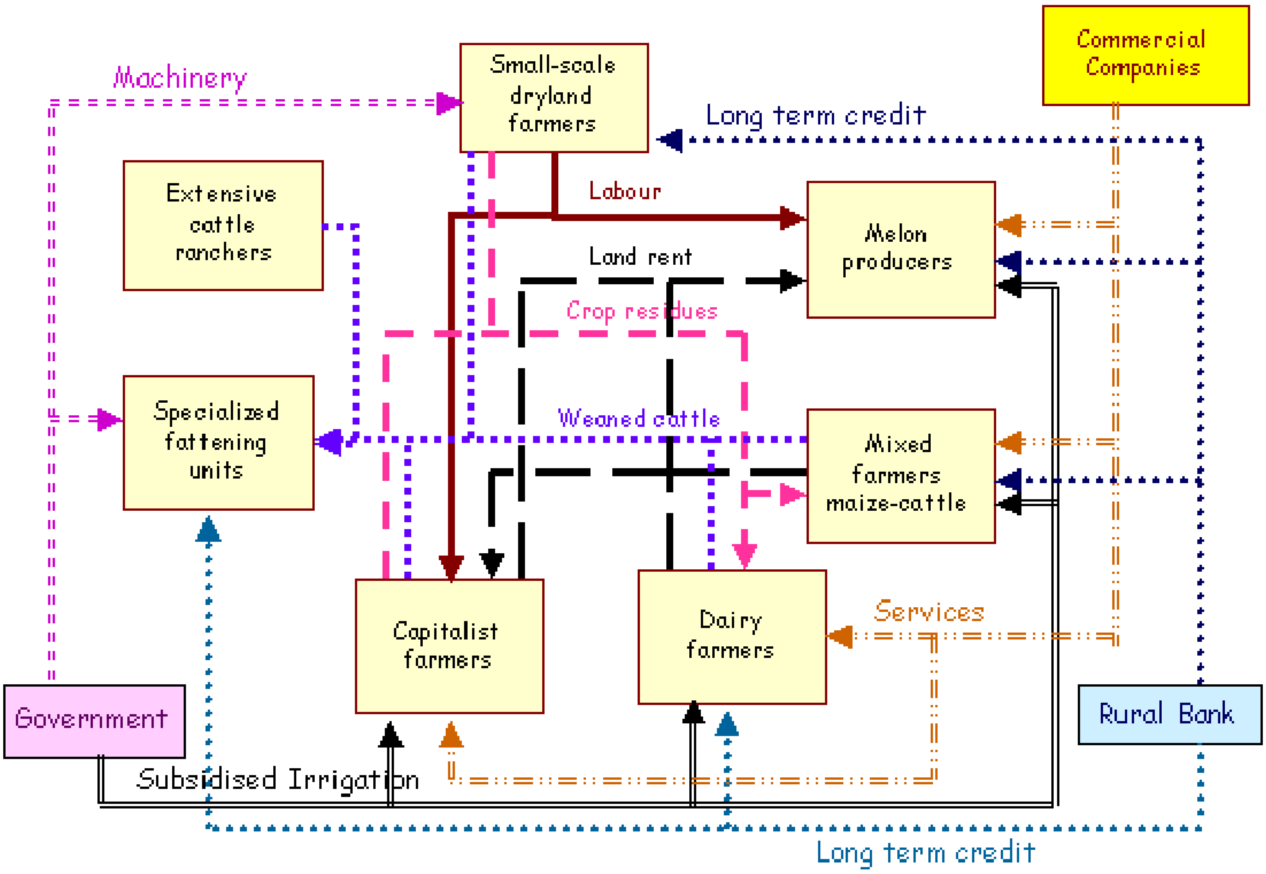

Fig. 18. Regional scale flow diagram

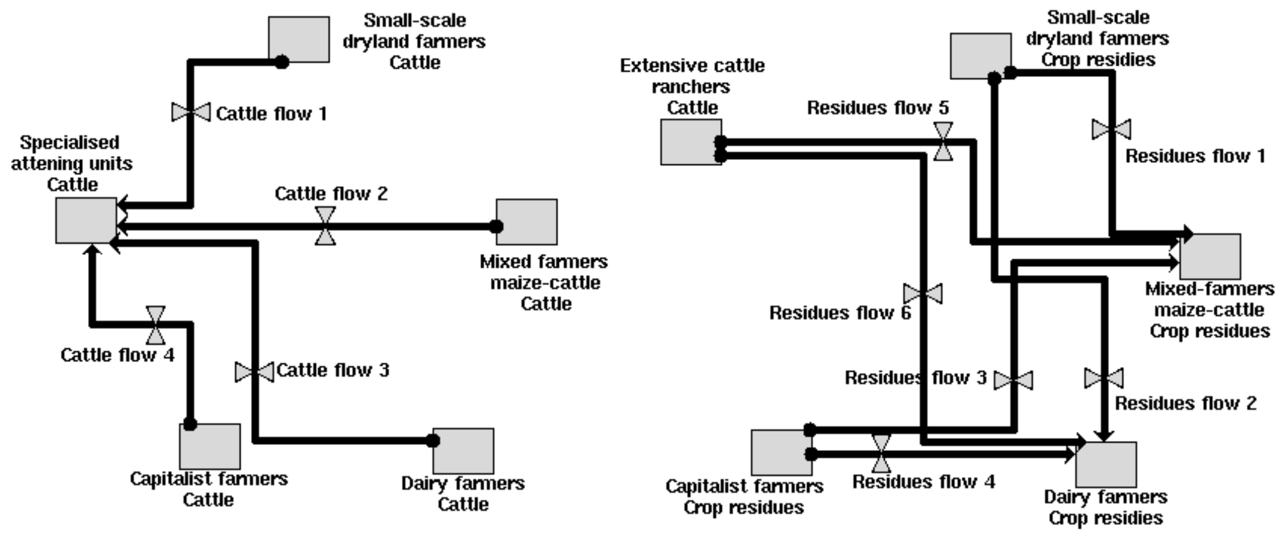

Fig. 19. The regional scale flow model in Simile (flows of Cattle and Crop residues only)

Fog. 19 shows one possible way of mapping the informal diagram in Fig. 18 into System Dynamics flow notation, using Simile as the particular modelling environment. In this solution, the flow pathways for the different substances are separated out, to avoid the visually-confusing appearance of lots of flow arrows crossing over each other. An alternative arrangement, following the approach used in the previous example, could have been to group all stocks relating to a single entity (farm type) together - i.e. to place the stocks 'Small-scale dryland farmers Cattle' and Small-scale dryland farmers Crop residues' next to each other. This would then be much closer to the original diagram. However, the resulting diagram would have had many Cattle flows overlapping many Crop residue flows. In the absence of an ability to colour flow arrows to indicate the substance they carry (as in the original diagram), this would have looked very messy. Note that this decision is cosmetic - it has no effect on the actual meaning of the diagram - but important nonetheless, since ease of communication is an important criterion.

It is legitimate to argue that the original diagram is actually clear and unambiguous, and that therefore it is a weakness of System Dynamics modelling software that it does not allow several stocks to be represented by a single block if no ambiguity results. This argument is valid if we are just considering stocks and flows. However, problems arise when we move on to full System Dynamics modelling, which includes a notation for showing which variables influence which others. If we want 'Dairy farmers Crop residues' to influence something else in the model, then it is hard to see how we could show this if 'Dairy farmers' were a single box, not separated into two separate stocks/

A2.3 Objects, hierarchical relationships and scaling

The following diagram (Fig. 20) is taken from Ericksen (2006) Fig. 4. It shows influences on food affordability coming from different scaling levels within a given system.

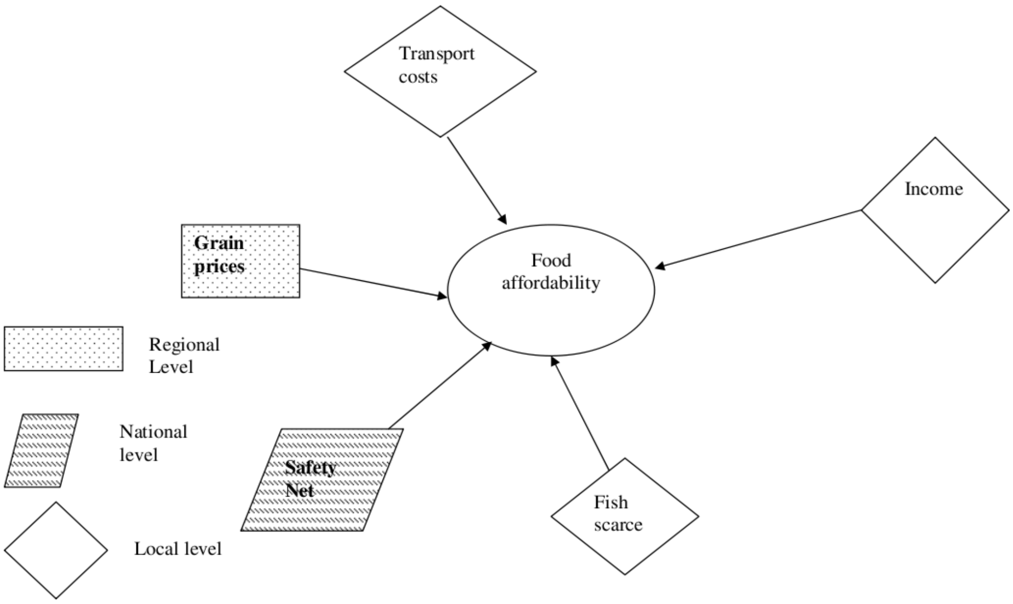

Fig. 20. Cross-scale diagram (Ericksen (2006) Fig. 4)

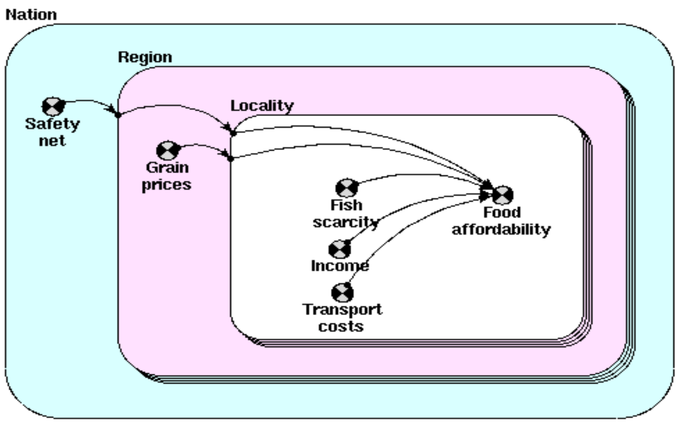

Fig. 21. Representation of cross-scale relationships in Simile

The Simile diagram (Fig. 20) conveys the same information as the original cross-scale diagram. The major difference is that the Simile diagram does this in a way which has a formal, standardised meaning, one which is immediately understandable by anyone who is familiar with the notation, and one which is amenable to computer processing. In contrast, the notation in the original diagram is specific to the author of the diagram, and it would not be possible to process the information conveyed by the diagram automatically.

Ingram (2009) proposes that a more sophisticated approach, based on multiple scales with multiple levels on each scale, and with interactions within and between scales, could be very useful in food security analyses. The following diagram (Fig. 22) is based on the figures in his presentation, and shows 3 scales - spatial, temporal and jurisdictional - with interactions between levels within a scale (blue) and between scales (red).

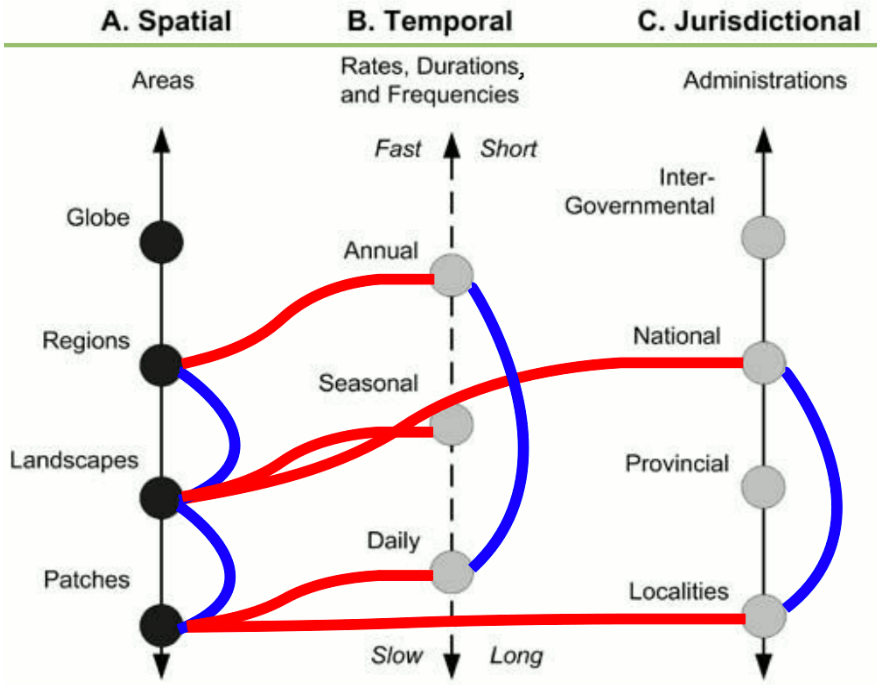

Fig. 22. Multiple scales, multiple levels within each scale. Within-scale interactions are shown in blue, and between-scale interactions in read. Derived from Ingram (2009).

Fig. 23 shows a Simile diagram which, I propose, captures the essence of the above diagram. The left-hand set of 3 nested submodels corresponds to the spatial scale, and shows a single region containing multiple landscapes, each of which contains multiple patches. The right-hand set of 2 nested submodels corresponds to the jurisdictional scale, and shows a single national jurisdiction containing multiple local jurisdictions.

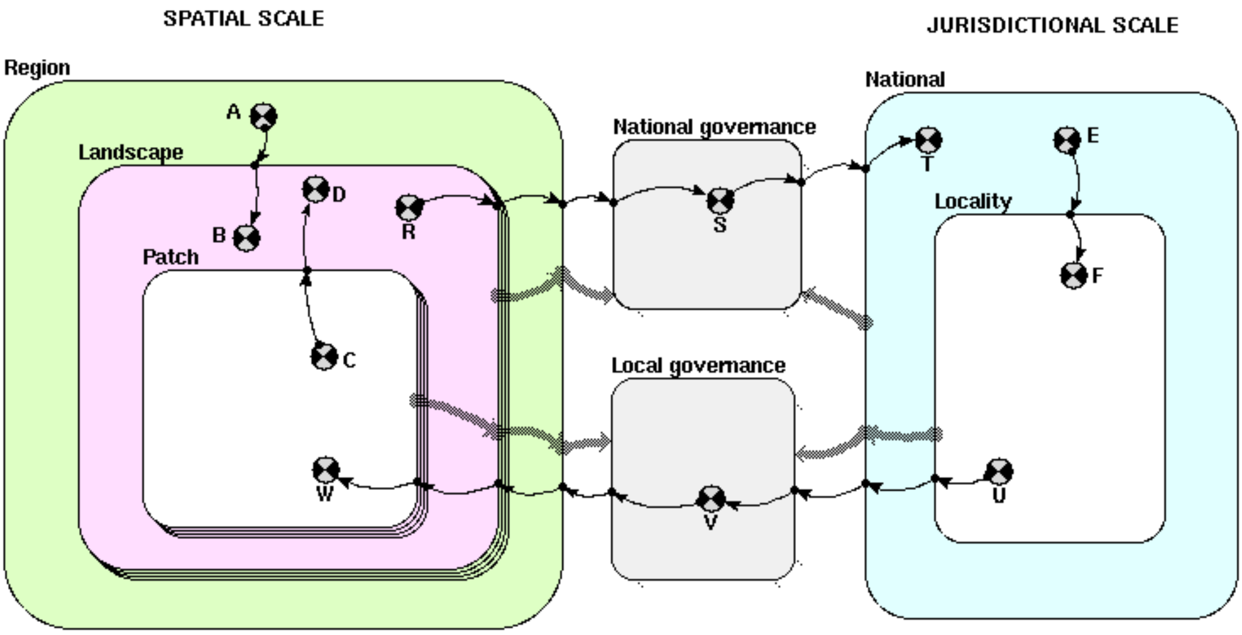

Fig. 23. Scales and levels expressed as a Simile diagram.

Links within a scale are shown as information flows between variables: A-B, C-D and E-F. Note that they can go in either direction (up-scale or down-scale). Links between scales are a little more complicated. They also involve the connection between variables, but this time are mediated through an "association submodel", which channels the information correctly to the required destination.

Note that it is assumed that the rather abstract "links between levels and between scales" of the original diagram is now translated into something concrete - the flow of information from one variable to another. It may be that a more sophisticated interpretation of this concept is required, but if so: what? In any case, it would seem that the idea of the flow of information between variables captures a good deal of what is required.

Note that the temporal scale is absent from the diagram. In fact, it is still supported by Simile: each submodel can be set to run on a different time scale, so in fact this scale is present - it's just that it is a property of a submodel rather than being a submodel in its own right .