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Theoretical Contribution

How we conceptualize climate change: Revealing the force-dynamic structure underlying stock-flow reasoning

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How people understand the fundamental dynamics of stock and flow (SF) is an important basic theoretical question with many practical applications. Such dynamics can be found, for example, in monitoring one's own private bank account (income versus expenditures), the state of a birthday party (guests coming versus leaving), or in the context of climate change (CO_2 emissions versus absorption). Understanding these dynamics helps in managing everyday life and in controlling behavior in an appropriate way (e.g., stopping expenditures when the balance of a bank account approaches zero). In this paper, we present a universal frame for understanding stock-flow reasoning in terms of the theory of force dynamics. This deep-level analysis is then applied to two different presentation formats of SF tasks in the context of climate change. We can explain why in a coordinate-graphic presentation misunderstandings occur (so called "SF failure"), whereas in a verbal presentation a better understanding is found. We end up with recommendations for presentation formats that we predict will help people to better understand SF dynamics. Better public SF understanding might in turn also enhance corresponding public action – such as enhancing pro-environmental actions in relation to climate change.

Keywords: force dynamics, stock-flow reasoning, climate change, causation, presentation format, dynamic problems

The dynamics of stock and flow represent a fundamental, abstract principle of nature: incoming objects are accumulated in a stock that keeps these objects for a certain period of time before they leave the stock by an outflow process. This abstract process description can be applied to species in a certain region (e.g., a given stock of birds has births as inflows and deaths as outflows), to the customers in a warehouse (e.g., a certain number of customers are at a given point in time in the store, new customers enter as inflows and satisfied customers leave as outflows), or to the daily food intake of persons (the current body weight representing the stock).

One stock-flow dynamics is of special interest for the survival of most species on planet earth: the greenhouse gases, especially the carbon dioxide (CO_2) emissions that contribute to global warming. Concerning CO_2 emissions into the atmosphere, a certain amount of emissions is added as inflow to the given stock in the atmosphere, the outflow dissolves mostly in the oceans or by means of photosynthesis. For more than 50 years, the balance between inand outflow seems to be disturbed by extreme increases of greenhouse gas emissions due to human activities (Intergovernmental Panel on Climate Change [IPCC], 2013).

Understanding such stock-flow (SF) processes is of great importance when one wants to control a given system (not only to beware a bathtub from overflow). Therefore, it is alarming to hear about the "SF failure" that has been reported repeatedly (Cronin, Gonzalez, & Sterman, 2009; Sterman & Sweeney, 2002, 2007): "Results from the experiments reported here demonstrate an important and pervasive problem in human reasoning: our inability to understand stocks and flows, that is, the process by which the flows into and out of a stock accumulate over time" (Cronin et al., 2009, p. 128).

Within the context of the climate change debate, the SF failure has important implications for the presentation of results (like those from the IPCC-reports) and for the possible implementation of educative measurements (Clayton et al., 2016). A deeper understanding of the SF failure seems therefore necessary particularly because recent work from Fischer, Degen, and Funke (2015) suggests that the SF failure might be an effect of the type of representation, i.e., how the information about stock and flow is presented to the participants. Our paper offers an explanation of the representation effects found by Fischer and colleagues in terms of a more fundamental analysis of SF reasoning processes. This analysis fleshes out the underlying causal structure that is inherent to SF reasoning.

Specifically, we (in section A) show for the first time how an SF problem (using atmospheric CO_2 accumulation as an example) can be described in terms of force dynamics, a prominent theory of causal cognition (e.g., Stocker, 2014; Talmy, 2000). Moreover, we examine (in sections B–D) how well scientific presentation formats comprising coordinate systems and graphs, verbal formats, and pictorial-schematic formats of presenting an SF problem (exemplified by atmospheric CO_2 accumulation) represent the force-dynamic structure underlying basic SF reasoning. Our central argument is: the better the formats represent the underlying force-dynamic structure of the SF problem, the better people can understand it. Finally (in section E) the implications of these differences of how well the underlying force-dynamic structure of SF CO_2 accumulation is represented in these different formats are discussed.

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A. The force-dynamic structure of conceptualizing stock-flow CO_2 accumulation

A most basic SF system consists of one inflow, one outflow, and one stock (Sterman & Sweeney, 2002, 2007; Fischer et al., 2015). In this section the basic force-dynamic structure underlying SF reasoning is exemplified with atmospheric CO_2 level. People often prefer to make use of the underlying causal structure to understand SF reasoning (Brehmer, 1976; Fischer et al., 2015; Garcia-Retamero, Wallin, & Dieckmann, 2007; Gonzalez, 2004). As a starting point to reveal the basic causal – force-dynamic – structure of atmospheric CO_2 level SF relations, consider the following two sentences adapted from Fischer and colleagues (2015, p. 13). These sentences highlight the basic causal relations involved in increase and decrease of atmospheric CO_2 level:

(1) *Examples of informal causal verbalizations of SF reasoning (exemplified with atmospheric CO_2 level)*

a. CO_2 emissions are caused by the burning of fossil fuels and increase atmospheric CO_2 concentration.

b. CO_2 absorptions are caused by forests and oceans and decrease atmospheric CO_2 concentration.

Naturally, the stock will increase if the inflow is greater than the outflow, decrease if the outflow is greater than the inflow, and remain constant if there is an equal amount of in- and outflow. If one puts these increase/decrease SF reasoning mechanisms into a slightly formalized verbal format, one notices that causality is involved at two different hierarchical levels:

(2) *The basic causal structure of SF reasoning in slightly formalized verbal format (exemplified with atmospheric CO_2 level)*

a. The burning of fossil fuels **causes$_{\textbf{level-1}}$** atmospheric CO_2 concentration to increase.

b. Absorption mechanisms of forests and oceans **cause$_{\textbf{level-1}}$** atmospheric CO_2 concentration to decrease.

c. Larger increase of atmospheric CO_2 concentration [increase which is **caused$_{\textbf{level-1}}$** by the burning of fossil fuels] than decrease of atmospheric CO_2 concentration [decrease which is **caused$_{\textbf{level-1}}$** by absorption mechanisms of forests and oceans] **causes$_{\textbf{level-2}}$** atmospheric CO_2 concentration to increase.

d. Larger decrease of atmospheric CO_2 concentration [decrease which is **caused$_{\textbf{level-1}}$** by absorption mechanisms of forests and oceans] than increase of atmospheric CO_2 concentration [increase which is **caused$_{\textbf{level-1}}$** the burning of fossil fuels] **causes$_{\textbf{level-2}}$** atmospheric CO_2 concentration to decrease.

e. Equal increase of atmospheric CO_2 concentration [increase which is **caused$_{\textbf{level-1}}$** by the burning of fossil fuels] and decrease of atmospheric CO_2 concentration [decrease which is **caused$_{\textbf{level-1}}$** by absorption mechanisms of forests and oceans] **causes$_{\textbf{level-2}}$** atmospheric CO_2 concentration to remain constant.

Taking (2c) as an example, we can notice the embedded causal hierarchy that is underlying basic SF reasoning: in order to capture basic SF reasoning in a full-fledged way, one must not only understand the causes of the increase and decrease (here termed level-1-causality), but one must also understand that the relationship between increase and decrease (e.g., increase is higher than decrease) of course also has causal consequences (here termed level-2-causality; e.g., increase is higher than decrease causes stock to rise). Abstracting away from (2), we can also outline the generic causal structure of SF reasoning:

(3) *The generic causal structure of SF reasoning in slightly formalized verbalized format*

a. A **causes$_{\textbf{level-1}}$** stock to increase.

b. B **causes$_{\textbf{level-1}}$** stock to decrease.

c. Larger amounts of inflow [inflow which is **caused$_{\textbf{level-1}}$** by A] than outflow [outflow which is **caused$_{\textbf{level-1}}$** by B] **cause$_{\textbf{level-2}}$** stock to increase.

d. Larger amounts of outflow [outflow which is **caused$_{\textbf{level-1}}$** by B] than inflow [inflow which is **caused$_{\textbf{level-1}}$** by A] **causes$_{\textbf{level-2}}$** stock to decrease.

e. Equal amounts inflow [inflow which is **caused$_{\textbf{level-1}}$** by A] and outflow [outflow which is **caused$_{\textbf{level-1}}$** by B] **causel$_{\textbf{evel-2}}$** the stock to remain constant.

What are the basic mental elements (basic building blocks) that make up SF reasoning? The conceptualization of cause and effect has long been treated (and often still is) as if cause and effect are themselves conceptual primitives – two conceptual "atoms" that do not consist of still further smaller elements (e.g. Goldvarg & Johnson-Laird, 2001; Pearl, 2000; Spirtes, Glymour, & Scheines, 2000). However, with the advent of the theory of force dynamics – a by now prominent theory of causal cognition that has initially been proposed by Talmy (e.g., Stocker, 2014; Talmy, 2000) – it has been possible to demonstrate that cause and effect can be described as consisting of still smaller conceptual elements (see below). In analogy, cause and effect are more like conceptual "molecules" that consist of conceptual "atoms", rather than being atoms themselves.

That causation represents force-dynamic thinking patterns has also been supported by experimental findings (Barbey & Wolff, 2007; Wolff, 2003, 2007; Wolff & Song, 2003). Stocker (2014) has offered a substantial revision of the original force-dynamic account as developed by Talmy (1985, 1988, 2000). This revision makes it possible that force dynamics can be applied to all causation, no matter how concrete or abstract the entities that are involved in the causation are (with the framework developed by Talmy it was not clear, how force dynamics could be applied for certain abstract entities). This modern version of force dynamics is called *elementary force dynamics* (Stocker, 2014) because it places a strong emphasis on identifying the elements (conceptual primitives) that make up a cause and the elements that make up an effect. First we introduce the basics of elementary force dynamics with a classic example from Talmy. Then we will demonstrate how elementary force dynamics can also be used to describe basic "elementary" SF reasoning, using atmospheric CO_2 accumulation as an example.

A.1. Force dynamics: General elements of the theory

Both classic force dynamics (Talmy, 2000) and elementary force dynamics (Stocker, 2014) involve the assumption that mental representation of causation involves the conceptualization of two opposed entities that are engaged in a force interaction. All general elements of the force-dynamic theory explained in this section stem from theoretical cognitive-linguistic work (Stocker, 2014; Talmy, 2000). For a linguistic exemplification, consider the following sentence adapted from Talmy (2000, p. 416):

(4) The ball started rolling because of the wind.

In a force-dynamic terms, the *ball* functions as the *agonist (Ago)*.[1] In elementary force dynamics (Stocker, 2014), Ago is a cognitive entity which can take on any given state or action. In (4) Ago is the *ball*, which initially takes on the state-value *stationariness* (if there were no wind, the ball would not be moving). The opposed conceptualized force entity is referred to as the *antagonist (Ant)* in force-dynamic theory. In (4) the *wind* takes on the Ant function. In elementary force dynamics, Ant is always conceptualized as attempting to impose a state or action onto Ago that is *different* from the outset action or state of Ago. Thus, when Ago is initially associated with stationariness, Ant will by definition try to impose a value or state other than stationariness. Hence in (4) the wind carries a different force value than the ball: Ant carries the force value *motion*, trying to impose this onto the inert ball. The resultant (effect) of a force-dynamic interaction always relates to Ago. The resultant depends on which of the force entities – Ago or Ant – is conceptualized as being stronger. In causation types that can be phrased with *because (of)*, as in (4), Ant is always conceptualized as being stronger.[2] Consequently, in (4) the force of Ant (the wind's motion force) is stronger than force of Ago (the ball's inert force). Thus, the ball is conceptualized as having been moved by the wind. Stocker (2014) has introduced a specific formal system to describe force-dynamic interactions (which is an abstraction of Talmy's original force-dynamic diagramming system). For a force-dynamic interaction underlying the linguistic use of words like "because" or "caused" (formally termed CAUSE or *successful causation*), the notational system looks as follows:

(5) **C:** Ago-x, Ant-x_{diff}(++) →
E: Ago-x_{diff}

C stands for cause and *E* for effect. In elementary force dynamics, Ago can initially be associated with any given state or action value (value "x"). In contrast, Ant's value must by definition be a state or action value that differs from x ("x_{diff}" where *diff* stands for different). Ant attempts to impose its different value onto Ago. As Ant's force is stronger than Ago's force in *because* ("++" stands for stronger[3]), the effect *E* is that Ago has to take on the different force value of Ant (→ E: Ago-x_{diff}). The content of (4) is force-dynamically distributed as follows (following notational convention, the content of (4) is added to the force-dynamic formula of (5) in underlined subscript):

(6) **C:** $\text{Ago}_{\underline{\text{ball}}}$-$x_{\underline{\text{stationariness}}}$, $\text{Ant}_{\underline{\text{wind}}}$-$x_{\text{diff}\underline{\text{motion}}}$(++) →
E: $\text{Ago}_{\underline{\text{ball}}}$-$x_{\text{diff}\underline{\text{motion}}}$

(6) reads: the cause C involves conceptualizing the ball in the function of Ago with the initial state value (x) of being stationary. Ago is weaker than Ant (the wind). Ant is conceptualized as imposing the different value (x_{diff}) of motion onto Ago (the ball). As Ant's imposing motion is conceptualized as being the stronger (++) force than Ago's inert force, the cognized effect E is indeed that the wind (Ant) causes the ball (Ago) to move.

A.2. Force dynamics applied to stock-flow reasoning

As a novel contribution to the study of stock-flow reasoning, it is now shown that the force-dynamic elements in (5) readily offer themselves to capture the basic causal mechanisms that are at work in stock-flow reasoning. (7) lays out all the force-dynamic elements that are involved in SF reasoning – exemplified in relation to how people conceptualize climate change (the details of (7) will become clear as the analysis proceeds).

(7) *The force-dynamic elements of SF reasoning (exemplified with atmospheric CO_2 level)*
   a. Agonist (Ago): stock (atmospheric CO_2 level)
   b. Antagonist_1 (Ant_1): stock increaser (burning of fossil fuels)
   c. Antagonist_2 (Ant_2): stock "decreaser" (absorption mechanisms of forests and oceans)
   d. x-state: at a certain level
   e. x_{diff}-action_1: increase level
   f. x_{diff}-action_2: decrease level
   g. x_{diff}-action_3: remain level
   h. stronger than (++)
   i. larger than (>)
   j. equal to (=)

Looking at (7), we may note that it is proposed that the stock can always be conceptualized as Ago (7a; atmospheric CO_2 level), and the forces that increase or decrease the stock always as Ant (7b–c; the burning of fossil fuels as an atmospheric-CO_2-level increaser, and absorption mechanisms of forests and oceans as an atmospheric-CO_2-level "decreaser"). The initial conceptualized state of Ago (atmospheric CO_2 level) before the intervention of Ant is always to be at a certain level (7d). Force interaction that results in increase, decrease or no increase/decrease of the stock (of atmospheric CO_2 level) always involves Ant trying to intervene with Ago's state (7e–g), and depending on whether Ago or Ant is conceptualized as stronger (7h), the end result relates to either a change of stock amount – more increase than decrease or more decrease than increase (7i) – or no change of stock amount (7j). It is now shown how the elements of (7) can capture level-1 causality and

[1] Talmy (2000) borrowed the terms agonist and antagonist from physiology, where these terms stand for members of specific opposed muscle pairs. In force dynamics, these terms are used in a different sense than in physiology (see Stocker, 2014).

[2] Ant is always stronger than Ago when the causal relationship can be phrased with words such as "caused", "because", "therefore", and the like. There are other forms where Ago is stronger then Ant, e.g. in „The ball did not roll *despite* the wind" (see Stocker, 2014).

[3] Talmy (2000) uses the symbol "+" to represent the force-dynamic meaning *stronger than*. However, since this symbol is already used in mathematics as a symbol to represent the meaning *plus* and since a few basic mathematical symbols (>, =) will later on in this article be used in a force-dynamic context, we use "++" to represent the force-dynamic meaning *stronger than* so as to avoid potential confusion with the mathematical meaning *plus*.

level-2 causality in their conceptual entirety. (8a) and (8b) represent force-dynamic reformulations of the slightly formalized verbal formats of (2a) and (2b), respectively (they represent level-1 causality).

(8) *Level-1 causality of SF reasoning in force-dynamic format exemplified with atmospheric CO_2 level*

a. **C:**
$Ago_{\underline{\text{atmospheric } CO_2\text{-concentration}}}\text{-}x_{\underline{\text{at-a-certain-level}}}$,
$Ant_{\underline{\text{burning of fossil fuels}}}\text{-}x_{\text{diff}\underline{\text{increase level}}}$ (++) →
E:
$Ago_{\underline{\text{atmospheric } CO_2\text{-concentration}}}\text{-}x_{\text{diff}\underline{\text{increase level}}}$
Verbalized: The burning of fossil fuels **causes$_{\text{level1}}$** atmospheric CO_2 concentration to increase.
Abbreviation:
EMISSION-CAUSES-CO_2-INCREASE

b. **C:**
$Ago_{\underline{\text{atmospheric } CO_2\text{-concentration}}}\text{-}x_{\underline{\text{at-a-certain-level}}}$,
$Ant_{\underline{\text{forests and oceans}}}\text{-}x_{\text{diff}\underline{\text{decrease level}}}$ (++) →
E:
$Ago_{\underline{\text{atmospheric } CO_2\text{-concentration}}}\text{-}x_{\text{diff}\underline{\text{decrease level}}}$
Verbalized: Absorption mechanisms of forests and oceans **cause$_{\text{level1}}$** atmospheric CO_2 concentration to decrease.
Abbreviation:
ABSORPTION-CAUSES-CO_2-DECREASE

(8a) suggests that the atmospheric CO_2 concentration is force-dynamically conceptualized as *Ago*. Naturally, before any CO_2 concentration increasing or decreasing force interferes, the CO_2 concentration is conceptualized as being *at a certain level* – thus “at a certain level” functions as the x-value of Ago. In (8a), the role of *Ant* is taken on by the *burning of fossil fuels*. Recall that in elementary force dynamics, Ant is by definition conceptualized as having a value different from the one of Ago which it tries to impose onto Ago. Here, Ant carries within it the force value (x_{diff}) of *increasing* Ago’s (CO_2 concentration’s) initial state of remaining at a certain level. The burning-of-fossil-fuel’s (Ant’s) force of increasing the CO_2 concentration is conceptualized as being stronger (++) than the CO_2 concentration’s basic state of remaining at a certain level. All this – cognizing the CO_2 concentration’s (Ago’s) initial state (the state before any forces act upon Ago) as *being at a certain level* and cognizing a stronger Ant force that imposes an increasing-level force onto Ago – represents the force-dynamic cause C. Thus, given that Ant is conceptualized as being stronger than Ago, the cognized effect E is indeed that the burning of fossil fuels (Ant) causes the CO_2 concentration (Ago) to rise. As will be seen, the whole force-dynamic conceptualization of (8a) will become part of still larger force-dynamic conceptualizations in SF reasoning. In relation to this, it will be convenient, if we can abbreviate (8a). Thus an abbreviation is already introduced: EMISSION-CAUSES-CO_2-INCREASE (please recall that this abbreviation stands for the entire force-dynamic structure (8a)).

Force-dynamically (8b) reads very similarly to (8a) as it is only some content values that change. The Ago at the outset is the same in (8b) as in (8a): the cause (C) again involves cognizing the CO_2 concentration’s (Ago’s) initial state (the state before any forces act upon Ago) as *being at a certain level*. But this time Ago’s initial state is conceptualized as being intervened by a different Ant: this time the *forest and ocean absorption mechanisms* function as Ant and as such Ant is carrying within it the force to *decrease* Ago’s initial state of remaining at a certain level. As Ant is again stronger (++) than Ago, the conceptualized effect (E) is this time that CO_2 concentration *decreases*. Formally (8b) is abbreviated to: ABSORPTION-CAUSES-CO_2-DECREASE (please recall that this abbreviation stands for the entire force-dynamic structure (8b)).

As already shown in (2), the basic causal structure of SF reasoning involves a two-level causal hierarchy. So far, we have examined level-1 causality from a force-dynamic viewpoint. Level-2 causality now involves force-dynamically to conceptualize atmospheric CO_2 increase with the following formulation for (2c), where CO_2 increase is larger than decrease:

(9) *Level-2 causality (increase > decrease) of SF reasoning in force-dynamic format exemplified with increasing atmospheric CO_2 level (with abbreviations)*

C:
$Ago_{\underline{\text{atmospheric } CO_2\text{-concentration}}}\text{-}x_{\underline{\text{at-a-certain-level}}}$,
Ant: [EMISSION-CAUSES-CO_2-INCREASE > ABSORPTION-CAUSES-CO_2-DECREASE] $x_{\text{diff}\underline{\text{increase level}}}$ (++) →
E:
$Ago_{\underline{\text{atmospheric } CO_2\text{-concentration}}}\text{-}x_{\text{diff}\underline{\text{increase level}}}$
Verbalized: Larger increase of atmospheric CO_2 concentration [increase which is **caused$_{\text{level1}}$** by the burning of fossil fuels] than decrease of atmospheric CO_2 concentration [decrease which is **caused$_{\text{level1}}$** by absorption mechanisms of forests and oceans] **causes$_{\text{level2}}$** atmospheric CO_2 concentration to increase.

Thus, Ago in (9) is still (as in all other examples) the atmospheric CO_2 concentration. The role of Ant is now force-dynamically complex: Ant now stands for “increase is higher than decrease” (where increase and decrease themselves also have a cause, as captured by the formal abbreviations; the larger-than relation is represented with the standard mathematical symbol for this, >). This semantically complex Ant (increase > decrease) naturally carries within it the force of *increasing* Ago’s (CO_2 concentration’s) initial state of remaining at a certain level. Thus, given that Ant is conceptualized as being stronger than Ago, the cognized effect E is that *increase > decrease* causes the CO_2 concentration (Ago) to rise. The two remaining SF level-2-causality possibilities (CO_2 decrease or CO_2 remaining constant) can be formally captured in very similar ways to (9):

(10) *Level-2 causality (decrease > increase; increase = decrease) of SF reasoning in force-dynamic format exemplified with decreasing and constant atmospheric CO_2 level*

a. **C:**
$Ago_{\underline{\text{atmospheric } CO_2\text{-concentration}}}\text{-}x_{\underline{\text{at-a-certain-level}}}$,
Ant:
[ABSORPTION-CAUSES-CO_2-DECREASE > EMISSION-CAUSES-CO_2-INCREASE]$x_{\text{diff}\underline{\text{decrease level}}}$ (++) →
E:
$Ago_{\underline{\text{atmospheric } CO_2\text{-concentration}}}\text{-}x_{\text{diff}\underline{\text{decrease level}}}$
Verbalized: Larger decrease of atmospheric CO_2 concentration [decrease which is **caused$_{\text{level1}}$** by absorption mechanisms of forests and oceans] than increase of atmospheric CO_2 concentration [increase which is **caused$_{\text{level1}}$**

by the burning of fossil fuels] $\mathbf{causes_{level2}}$ atmospheric CO_2 concentration to decrease.

b. **C:**
$\text{Ago}_{\text{atmospheric } CO_2\text{-concentration}}\text{-x}_{\underline{\text{at-a-certain-level}}}$,
Ant: [EMISSION-CAUSES-CO_2-INCREASE = ABSORPTION-CAUSES-CO_2-DECREASE]
$\text{x}_{\text{diff}\underline{\text{remain level}}}$ (++) →
E:
$\text{Ago}_{\text{atmospheric } CO_2\text{-concentration}}\text{-x}_{\text{diff}\underline{\text{remain level}}}$
Verbalized: Equal increase of atmospheric CO_2 concentration [increase which is $\mathbf{caused_{level1}}$ by the burning of fossil fuels] and decrease of atmospheric CO_2 concentration [decrease which is $\mathbf{caused_{level1}}$ by absorption mechanisms of forests and oceans] $\mathbf{causes_{level2}}$ atmospheric CO_2 concentration to remain constant.

Thus, in (10a) the complex Ant represents the relationship *decrease* > *increase* which imposes the force onto Ago (atmospheric CO_2 level) of decreasing CO_2 level, and in (10b) Ant represents the relationship *increase* = *decrease* which imposes the force onto Ago (atmospheric CO_2 level) of keeping the CO_2 level at a constant level.

In sum, in this section it has been shown how the force-dynamic elements of (7) can fully flesh out the complex causal mechanisms that underlie SF reasoning. In the following sections, different presentation formats for stock-flow CO_2 accumulation will be investigated to see how well they represent (3), 2-level causality, and (7), the basic causal elements of SF reasoning. We will argue that the better the presentation format for stock-flow reasoning represents the underlying force-dynamic structure, the better people can understand stock-flow reasoning (in the following sections exemplified with CO_2 accumulation).

B. Pictorial-schematic presentation format for stock-flow CO_2 accumulation

As Fischer and colleagues write:

> The structure of SF systems is often explained by a bathtub analogy: The water level (stock) in a bathtub increases if the inflow of water through the faucet exceeds the outflow through the drain; the water level drops if the outflow exceeds the inflow (2015, p. 2).

This bathtub analogy readily lends itself to a pictorial-schematic presentation format for SF CO_2 accumulation. Thus, in order to investigate how well a pictorial bathtub analogy of SF reasoning can represent the underlying force-dynamic structure, we have devised such a pictorial-schematic presentation (see Figure 1). This is how we intuitively would present the bathtub analogy in a pictorial-schematic presentation format; future studies would have to determine if there is an optimal way of how to represent the bathtub analogy for climate change in a pictorial-schematic format.

All pictorial-schematic elements of stock-flow CO_2 accumulation in Figure 1 have their ready analogues to potential water increase or decrease in a bathtub: instead of an increasing, decreasing, or constant water level in a bathtub container, we have an increasing, decreasing, or constant CO_2 level in an "atmosphere container"; instead of water entering and leaving a bathtub, we now have CO_2 "entering and leaving" the atmosphere; instead of larger/smaller amounts of inflow and outflow of water, we have larger/smaller amounts of inflow and outflow of CO_2 (larger/smaller amounts of in- and outflow are depicted by smaller and larger arrows, respectively).

As a basic guide to analyze the causal force-dynamic content of Figure 1 we first use (3). This will allow us to check whether the pictorial-schematic representation of SF reasoning in Figure 1 explicitly represents *two-level* causality. Then (7) – the force-dynamic elements of SF reasoning – will be used as a force-dynamic check to examine whether a pictorial bathtub analogy of SF reasoning (Figure 1) can represent all force-dynamic elements that are involved in basic SF reasoning.

As examined in (3), *SF level-1 causality* involves the two basic causal relationships. First in level-1 causality (3a), A (i.e., Ant_1) increases the stock (Ago). Figure 1(a–c) depicts this with an arrow pointing into the stock (labeled "CO_2 IN (EMISSION: burning of fossil fuels)"), suggesting CO_2 increase in the atmosphere. Second in level-1 causality (3b), B (i.e., Ant_2) decreases the stock (Ago). Figure 1(a–c) depicts this with an arrow pointing out of the atmosphere (labeled "CO_2 OUT (ABSORPTION: forests, oceans)"), suggesting CO_2 "leaving" the atmosphere.

As also examined in (3), *SF level-2 causality* involves three basic causal relationships: (3c) *increase* > *decrease* causes stock increase; (3d) *decrease* > *increase* causes stock decrease; and (3e) *increase* = *decrease* causes stock to remain constant. In Figure 1, the > and = relationships are captured by the different sizes of both solid-line arrows. Thus, for instance, if (depicting (3a)) the inward-pointing arrow is larger than the outward-pointing arrow, then it can be deduced that this results in CO_2 increase (symbolized with the upward-pointing dotted arrow).

Force-dynamically we may furthermore note that Figure 1 depicts all ten force-dynamic elements that are involved in basic SF reasoning (cf. with (7)):

(11) *The force-dynamic elements of SF reasoning in the pictorial bathtub-analogy format (exemplified with atmospheric CO_2 level)*

a. Ago: *stock* (here *CO_2 level*) is pictorial-schematically represented by a dotted line symbolizing the CO_2 level which is complemented by the verbal label *CO_2 level*

b. Ant_1: *stock increaser* (emission) is pictorial-schematically represented by an inward-pointing arrow which is complemented with the verbal labels *CO_2 IN* and *EMISSION: burning of fossil fuels*

c. Ant_2: *stock "decreaser"* (absorption) is pictorial-schematically represented by an outward-pointing arrow which is complemented by the verbal labels *CO_2 OUT* and *ABSORPTION: forests, oceans*

d. x-state: being at a certain given level; pictorial-schematically represented by the horizontal orientation of the dotted CO_2 level line and by adding the verbal label *level* next to the verbal label *CO_2*

e. x_{diff}-action$_1$: *increase level* is pictorial-schematically represented by the dotted upward arrow which is complemented with the verbal label *increase*

f. x_{diff}-action$_2$: *decrease level* is pictorial-schematically represented by the dotted downward arrow which is complemented with the written label *decrease*

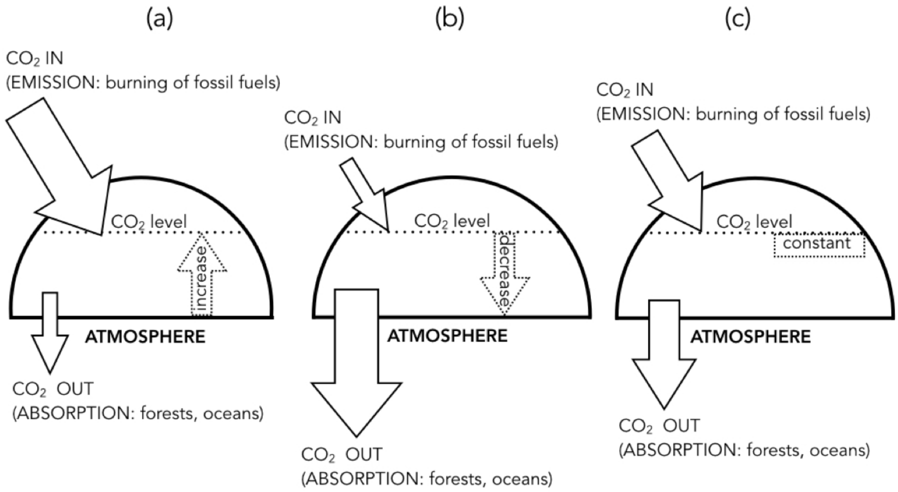

Figure 1. Pictorial-schematic presentation format for stock-flow CO_2 accumulation (based on the bathtub analogy). (a) More CO_2 gets in the atmosphere (symbolized by the larger inward-pointing arrow) than out (smaller outward-pointing arrow), resulting in CO_2 increase (upward-pointing arrow). (b) More CO_2 leaves the atmosphere (larger outward-pointing arrow) than comes in (smaller inward-pointing arrow), resulting in CO_2 decrease (downward-pointing arrow). (c) The same amount of CO_2 enters and leaves the atmosphere (symbolized by equal-sized inward- and outward-pointing arrows), resulting in a CO_2 concentration that remains constant (symbolized by a horizontal non-pointed strip).

g. x_{diff}-action$_3$: *remain level* is pictorial-schematically represented by the dotted horizontal non-pointed strip complemented with the written label *constant*
h. stronger than (++): is pictorial-schematically represented by placing the larger flow arrow to the stronger force entity and the smaller flow arrow to the weaker force entity (the force-relationship itself has no additional verbal label; it is thus only symbolized by symbolically suggesting that *stronger* = *larger* and *weaker* = *smaller*).
i. larger than (>): is (similar to h) pictorial-schematically represented by placing the larger flow arrow to the larger flow quantity and the smaller flow arrow to the smaller flow quantity
j. equal to (=): is pictorial-schematically represented by placing equally-sized flow arrows to the inflow and outflow quantities

Summing up the analysis of Figure 1, one can notice that the pictorial-schematic presentation format for stock-flow reasoning together with its complementing verbal labels depicts the causal structure of SF reasoning about CO_2 level in the atmosphere in its entirety: it depicts both levels of the causality hierarchy (level-1 and level-2 causality, cf. (3)) as well as all force-dynamic elements that make up basic SF reasoning (cf. (7)).

C. Verbal presentation format for stock-flow CO_2 accumulation

Consider the following verbal format (from Fischer et al., 2015) that is used to assess the understanding of lay people's SF understanding in the context of climate change:

12) *Verbal presentation format for stock-flow CO_2 accumulation*
CO_2 emissions are caused by the burning of fossil fuels and lead to an increase of atmospheric CO_2 concentration. CO_2 absorptions are caused by forests and oceans and decrease atmospheric CO_2 concentration. CO_2 emissions are currently twice as high as CO_2 absorptions. Imagine that emissions were reduced by 30%: How would the atmospheric CO_2 concentration react?
  a. Atmospheric CO_2 concentration would increase.
  b. Atmospheric CO_2 concentration would decrease
  c. Atmospheric CO_2 concentration would remain constant.

This format yielded high understanding of SF problems: the majority of the participants correctly inferred that as long as there is more CO_2 increase than decrease (which is what the scenario above suggests), CO_2 level rises. Let it now be examined how extensively (12) covers the underlying causal (force-dynamic) structure of basic SF reasoning. As with the pictorial-schematic format of the bathtub analogy which was examined in the previous section, first (3) serves again as a guide to analyze if both levels of the causality hierarchy (level-1 and level-2 causality) are represented; and then (7) is again used to see how extensively force-dynamic elements are represented.

The SF level-1 causal relation (3a) is clearly covered in (12) with the sentence "CO_2 emissions are caused by the burning of fossil fuels and lead to an increase of atmospheric CO_2 concentration". SF level-1 causal relation (3b) is also covered: "CO_2 absorptions are caused by forests and oceans and decrease atmospheric CO_2 concentration".

In (12), the *level-2-causality* relationship (3c) *increase > decrease* is covered by the two sentences "CO_2 emissions are currently twice as high as CO_2 absorptions. Imagine that emissions were reduced by 30%" as well, of course, as by the corresponding correct answer "Atmospheric CO_2 concentration would increase". The causal thinking that is behind the other two theoretically possible basic relationships – (3d: decrease > increase) and (3e: increase = decrease)– are covered by the (wrong) answers "Atmospheric CO_2 concentration would decrease" and "Atmospheric CO_2 concentration would remain constant", respectively.

In (12), how extensively are the force-dynamic elements that are involved in basic SF reasoning (cf. with (7)) rep-

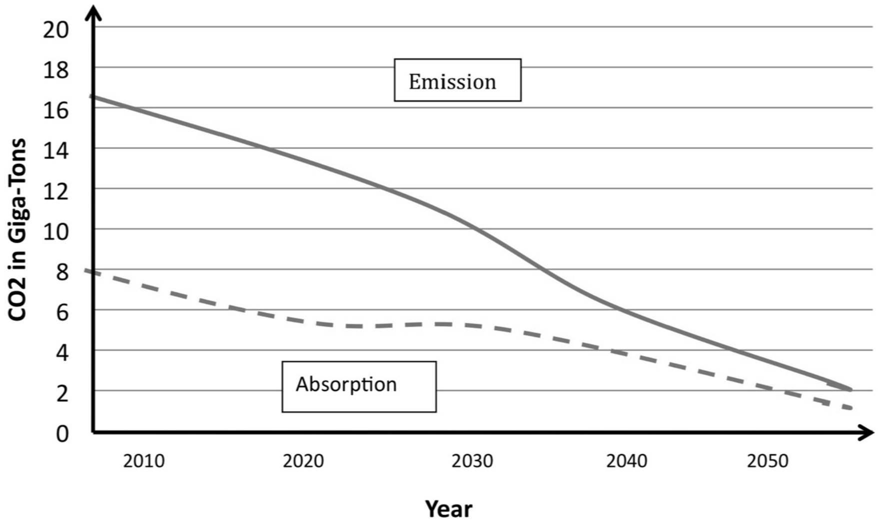

Figure 2. Coordinate-graphic presentation format for stock-flow CO_2 accumulation. The graph plots time on the x-axis and hypothesized amounts of atmospheric CO_2 in giga-tons on the y-axis. The predicted emission and absorption curves are plotted.

resented? This is shown in (13). If force-dynamic elements are missing, then this will be symbolized with "—" and "n.a." stands for *not applicable*.

(13) *The force-dynamic elements of SF reasoning in verbal format (exemplified with atmospheric CO_2 level)*

a. Ago: "CO_2 concentration"

b. Ant_1: "burning of fossil fuels"

c. Ant_2: "forests and oceans"

d. x-state: — ($x_{\underline{\text{at a certain level}}}$ has to be inferred)

e. x_{diff}-$action_1$: "CO_2 concentration would increase"

f. x_{diff}-$action_2$: "CO_2 concentration would decrease"

g. x_{diff}-$action_3$: "concentration would remain constant"

h. stronger than (++): n.a.

i. larger-than (>): n.a

j. equal-to (=): n.a.

Hence, we may note that (12) explicitly represents almost all force-dynamic elements that are involved in basic SF reasoning. What is not explicitly expressed in (12) is that Ago's (the CO_2 concentration's) state is conceptualized as being initially at a certain level (before any intervention takes place). However, given the high SF understanding that (12) has produced (Fischer et al., 2015), one may perhaps assume that the omission of this piece of information can easily be inferred. That relational information such as *increase > decrease* (13h–j) is not represented in (12), lies in the nature of the task. After all, the very nature of this task is for the participants to infer relevant relational information, such as increase > decrease, from the other given information.

In sum, in this section it has been shown that causal force-dynamic structure of SF reasoning about atmospheric CO_2 level is almost captured in its entirety by the verbal presentation format of Fischer and colleagues (2015) and that the one force-dynamic value missing – the x-state *at a certain level* – can probably be easily inferred.

D. Coordinate-graphic presentation format for stock-flow CO_2 accumulation

Figure 2 (as used in Fischer et al., 2015) shows one of the most common forms of how to represent stock-flow CO_2 accumulation in studies on understanding SF phenomena: a coordinate-graphic presentation format based on standard scientific representation norms (plotting a relation of two variables on an x- and y-axis). It is now examined how well the coordinate-graphic presentation format for stock-flow CO_2 accumulation represents the underlying causal structure of SF reasoning.

We may note that the graphic presentation of Figure 2 does neither depict level-1 causality (3a) nor level-1 causality (3b). Hence, neither the actual causal interplay between emission and CO_2 increase (how more emission leads to more CO_2) nor between absorption and CO_2 decrease (how more absorption leads to less CO_2) is depicted in the coordinate-graphic presentation.

Similarly, one also does not find level-2 causality relationships directly represented in the graph of Figure 2. Only part of the relationship (3c) "*increase > decrease* causes stock increase" can be logically inferred; for instance for 2050, by noticing that emission is still higher on the y-axis than absorption (this, of course, allows to infer "increase > decrease"). However, the causal consequence of this ("causes stock to increase") can no longer be inferred from the visual information given by the graph of Figure 2. Hence, while parts of level-2 causality can be logically inferred by inspecting the visual information in the graph, the actual causal consequences cannot be directly derived by solely inspecting the visual information in the graph.

Finally, we turn to the question: how extensively are the force-dynamic elements that are involved in basic SF reasoning (cf. with (7)) represented in Figure 2?

(14) *The force-dynamic elements of SF reasoning in the coordinate-graphic format (exemplified with atmospheric CO_2 level)*

a. Ago: "CO_2 in giga tons"

b. Ant_1: the plotted line labeled "Emission"

c. Ant_2: the plotted line labeled "Absorption"

d. x-state: — ($x_{\underline{\text{at a certain level}}}$ has to be inferred)

e. x_{diff}-$action_1$: — (in accompanying text only)

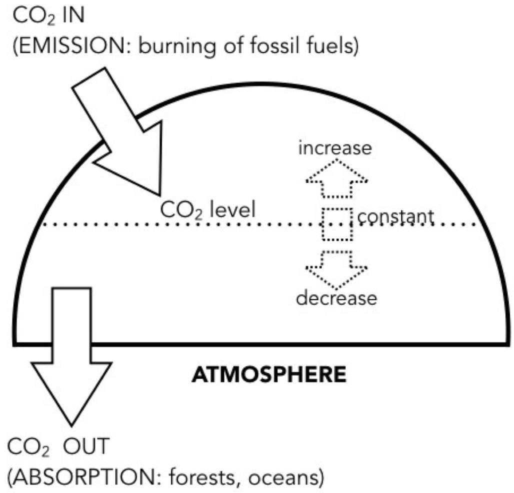

Figure 3. Pictorial-schematic presentation format for stock-flow CO_2 accumulation where increase/decrease/constancy has to be inferred. Could be combined with a verbal format.

f. x_{diff}-action$_2$: — (in accompanying text only)
g. x_{diff}-action$_3$: — (in accompanying text only)
h. stronger than (++): n.a.
i. larger-than (>):(++): n.a
j. equal-to (=): n.a.

The force-dynamic analysis of the graph in (14) is summarized quickly: the force-dynamic interaction between the Ago and the Ant is not represented because the action-values of the Antagonists (the powers that lead to increase, decrease, or constancy) are not represented in the graph. Therefore, none of the actual causal interplay between atmospheric CO_2 level and emission/absorption that leads to CO_2 increase is graphically displayed.

While the coordinate-graphic presentation format (14) displays the underlying causal relationships only marginally, it of course does display information that the pictorial-schematic presentation format (Figure 2) and the verbal presentation format (12) does not display: predictions of how levels of emission and absorption develop over time. Such information is of course vital and indispensable, also for the public. Thus, what might be at hand in order to optimize public understanding of climate change (cf. Introduction) is a synthesis of the coordinate-graphic, the verbal, and the pictorial-schematic format (see Discussion).

E. Discussion

In this article two main endeavors were undertaken. First, we developed a force-dynamic account of stock-flow reasoning and showed that our new theoretical approach to stock-flow reasoning can explain all basic cognitive aspects that are involved in stock-flow reasoning. Second, we carried out an analysis in terms of this new force-dynamic account for stock-flow reasoning in relation to three different modes of presentation of CO_2 accumulation: (a) the pictorial-schematic format of the bathtub analogy (as shown in Figure 1), (b) the verbal format (as shown in (12) and (13)), and (c) the coordinate-graphic format (as shown in (14) and in Figure 2). Force-dynamic theory explains why (b) produces better understanding than (c) because the necessary force-dynamic elements for a correct understanding are only present in (b). Thus, our force-dynamic account has the theoretical power to explain the empirical finding of Fischer and colleagues (2015) that a verbal format of stock-flow reasoning produces a better understanding than what studies using coordinate-graphic format (Cronin, Gonzalez, & Sterman, 2009; Sterman & Sweeney, 2002, 2007) have found.

Additionally, – as a new empirical question – we can also turn to the question how the bath-tube-analogy-based pictorial-schematic presentation format could be used to enhance understanding of SF reasoning (including understanding the SF reasoning about climate change). So far (in section B) we have only shown (see Figure 2) pictorial-schematic presentation formats that "give away" whether there will be stock increase, decrease, or constancy (because the purpose was to identify the underlying causal and force-dynamic structure and not to present ways how SF reasoning abilities might be tested). However, any investigation into basic SF reasoning skills must of course not give away what has been termed level-2 causality in this paper (increase > decrease causes stock increase; *decrease* > *increase* causes stock decrease; and *increase* = *decrease* causes stock to remain constant) – because it is just the correctness of these inferences that usually are tested when investigating how well people perform in SF reasoning (Cronin, Gonzalez, & Sterman, 2009; Fischer et al., 2015; Sterman & Sweeney, 2002, 2007).

Figure 3 gives one example of a pictorial-schematic presentation format for stock-flow CO_2 accumulation that does not give away level-2 causality.

The pictorial-schematic format in Figure 3 could for instance be combined with the verbal format of Fischer and colleagues (2015), with (12), to assess basic understanding of SF reasoning skills. Answering the questions in (12), participants in corresponding studies could use a graph among the lines of Figure 3 to think their answers through. As participants would be reading the addition ("twice as high") and subtraction ("reduced by 30%") information, they might for instance inspect the graph and might mentally project

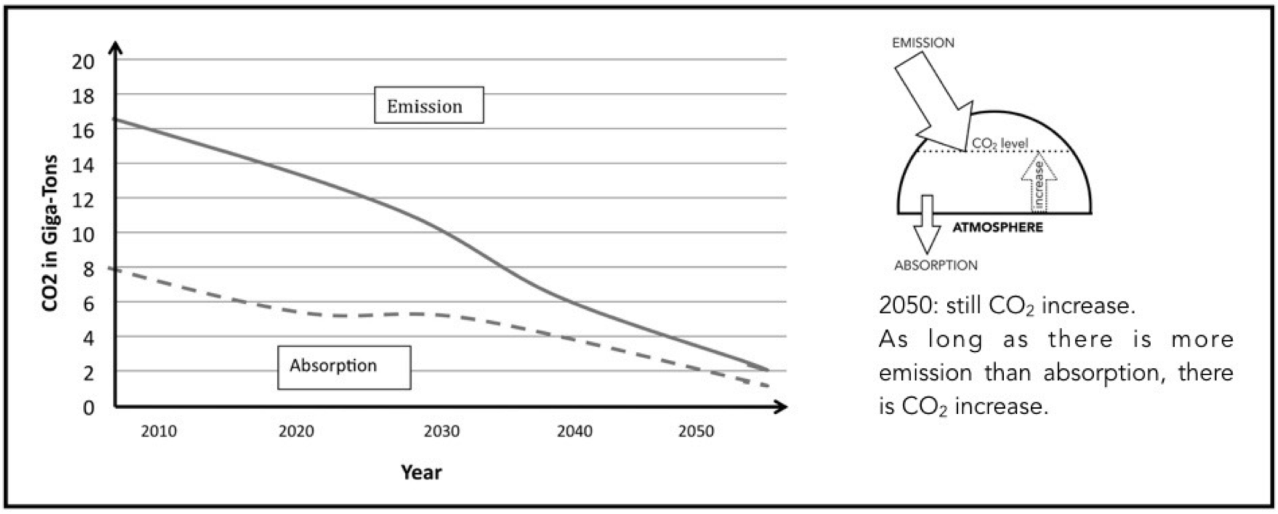

Figure 4. Pictorial-schematic complementation of the coordinate-graphic presentation format for stock-flow CO_2 accumulation. Furthermore, this combined format could also be presented together with an additional coordinate graph that shows the real, actual increase over the years.

corresponding higher and lower levels of CO_2 levels into the picture. Such a visual aid could possibly lead to still higher understanding of SF reasoning about climate change. Schematic visual information – like the one in Figure 3 that highlights more spatial relations than actual visual content – might indeed assist reasoning skills. People for instance do better in logical reasoning when little or no imagery is required, but when the problem can be cognized with a clear spatial layout (Knauff, 2013).

Finally: what could be done to counteract so called "SF failure" – the widespread wrong interpretations of SF problems that involve emission/absorption coordinate graphs (Cronin, Gonzalez, & Sterman, 2009; Sterman & Sweeney, 2002, 2007)? This is a very important question, as such coordinate graphs feature prominently in official reports about global warming (e.g., Intergovernmental Panel on Climate Change [IPCC], 2013). A simple attempt to counteract SF failure would be to add a pictorial-schematic presentation format of Figure 1 to the coordinate-graphic presentation format of Figure 3. A text that could be added to Fig. 1 is for instance: "2050. Still CO_2 increase. As long as there is more CO_2 emission than absorption, there is CO_2 increase". This is represented in Figure 4.

As shown in Figure 4, bringing together different presentation formats (*coordinate*, *pictorial-schematic*, which could furthermore be accompanied by *verbal*) could form a powerful synthesis that could possibly help a) researchers to more adequately assess basic stock-flow reasoning skills, and b) the public to better understand reasoning about climate change. Together with coordinate graphs showing the real increase over the years, this synthesis would allow representing future predictions of emission and absorption developments (SF coordinate format), while at the same time making the underlying force-dynamic (causal) structure transparent (SF verbal and pictorial-schematic format). Given the "relentless rise of carbon dioxide" (as NASA puts it[4]), and given the dangers that come with it for our planet, we should not too easily accept the "SF failure" of people as a scientific fact. Quite the opposite: we have offered a theoretical (force-dynamic) interpretation of an empirical finding (of Fischer and colleagues, 2015) that makes a strong case that – as long as the presentation formats for SF reasoning represents force-dynamic causal thinking patterns – people actually show large *SF competence*. SF competence might be a much more promising basis than SF failure to promote pro-environmental behavior among the human species in order to protect our planet.

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[4] https://climate.nasa.gov/climate_resources/24/

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