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How interactive simulations can improve the support of environmental management – lessons from the Dutch peatlands

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ABSTRACT

How interactive simulation systems can improve the support of environmental management is not fully understood. We therefore cross-analyzed questionnaires with logfiles and videos of workshops in which an interactive simulation system for peatland management was applied, to derive an in-depth perspective of its added values. The workshop participants explored the physical system dynamics, implementing measures, and the social system dynamics, brokering deals with other stakeholders. The system enabled capacity building at individual and group level, through iterative exploration of possible measures. As a result, cooperation among the stakeholders was enhanced and their understanding of problems and action perspectives regarding the peatlands was increased. Interventions that stimulated deliberation during the workshops were shown to prevent individualistic strategies, and instead fostered cooperative attitudes. The embeddedness in preceding Science–Policy Interfaces enhanced the credibility and legitimacy of the system, whereas salience was strengthened by abundant detailed information, realistic visual quality, and short calculation times.

1. Introduction

The sustainable management of social–ecological systems is notoriously complex because management strategies must address a set of interrelated environmental, political, and economic variables, with impacts across multiple spatial and temporal scales that are often nonlinear and highly uncertain (Walker et al., 2002; Ostrom, 2009). It is therefore widely acknowledged that management strategies must move beyond panaceas, instead adopting a perspective that embraces complexity (Folke, 2006; Ostrom, 2007). To effectively harness science for this challenge, interfaces are needed that promote communication and translation between experts and decision-makers and enable mediation to avoid tradeoffs between the salience, credibility, and legitimacy of the scientific information (Cash et al., 2003). These Science–Policy Interfaces are essentially social processes with the aim of enriching decision making (van den Hove, 2007); they encompass a variety of typologies, such as individual mediators, processes of participatory knowledge development, and boundary organizations (van Enst et al., 2014).

To bridge the gap between science and policy, many Science–Policy Interfaces use “boundary objects”, i.e., collaborative outputs that “are both adaptable to different viewpoints and robust enough to maintain identity across them” (Star and Griesemer, 1989). Examples range from GIS technology (Harvey and Chrisman, 1998) and simulation models (White et al., 2010) to multifaceted concepts like “ecosystem services” (Abson et al., 2014). Cash et al. (2003) suggest that collaborative efforts to produce boundary objects are likely to result in credible, legitimate, and salient information.

However, van Enst et al. (2014) point out that Science–Policy Interfaces may encounter several interaction problems that diminish their effectiveness. In their paper they illustrate how operational misfits between the demand and supply of knowledge will reduce the salience of information, and how strategic production and/or use of knowledge will also negatively impact the credibility and legitimacy of knowledge. The strategical interaction problems mainly occur when the knowledge is uncertain and/or consensus on norms and values is lacking. The operational misfits occur more often. For example, Uran and Janssen (2003) describe how many Decision Support Systems failed to provide salient information for their users and were therefore not used as effective boundary objects. Leskens et al. (2014a) describe how simulation models for flood disaster management encountered similar predicaments, mainly because the models needed experts to run them and could not keep pace with the speed of interactions in the decision-making processes.

In an extended literature review, Mayer (2009) describes how operational misfits and the accompanying critiques stimulated many

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developers of simulation models to create more transparent and interactive models that are more likely to become effective boundary objects. He argues that serious games can be regarded as the most promising exponent of this new generation of computer-mediated support systems, because they are able to integrate the technical–physical and the social–political complexities of policy problems. In addition, serious gaming is known to be an effective technique for learning and retention (Hofstede et al., 2010; Connolly et al., 2012; Wouters et al., 2013; Cheng et al., 2017), with proven abilities to engage stakeholders and allow them to experience the complexity of collaborative management tasks (Bekebrede, 2010; Vervoort et al., 2014). Not surprisingly, serious games are increasingly being used to support the management of social–ecological systems (e.g., van der Wal et al., 2016; Voinov et al., 2016; Craven et al., 2017). For similar reasons, many contemporary Decision Support Systems allow for interactive simulations too; they include spatial decision support tools such as "Touch Tables" (Arciniegas et al., 2013; Eijkelboom and Janssen, 2013; Pelzer et al., 2016), and flood simulation models (Leskens et al., 2014b). For terminological clarity, in this paper we will refer to all interactive computer-mediated support systems as "interactive simulation systems" (ISS).

Despite the potential benefits of ISS, it is unclear to what extent they effectively support management decisions, because much ISS research is hampered by one or more limitations. First, many ISS are tested with the help of students instead of real-world stakeholders (e.g., Hummel et al., 2011; Poplin, 2012; Arciniegas et al., 2013; Schulze et al., 2015). This raises the issue of external validity: it remains uncertain to what extent these settings reflect real-world practices. Moreover, the ISS test results of students have been shown to differ significantly from those of professional stakeholders (Bekebrede et al., 2015). Second, most studies consider only one or a limited number of workshops. Although this might provide valuable results, it remains uncertain to what extent the results can be generalized to other circumstances. Third, most studies focus on opinions voiced by the participants in workshops in which the ISS was tested, without considering logfiles and/or video recordings of the workshops. The disadvantage of stated opinions is that answers can be biased, e.g., by socially preferred answers. Logfiles and/or video recordings lack these possible biases, because they reveal not what people say but how they actually behave in the workshops in which the ISS is tested.

In this paper, we report research that aimed to overcome the research limitations mentioned above. We tested an ISS with real-world stakeholders in multiple workshops, using questionnaires, as well as logfiles and video recordings of the workshops. The guiding research question was: How can ISS improve the support of environmental management?

2. Method

2.1. Outline research

The case we used for our research was the collective management of Dutch peatlands. At the turn of the century, it was suggested to raise the surface water levels, which would decrease the soil subsidence rates. Although profitable dairy farming would no longer be possible and large-scale transitions from dairy farming to nature restoration would be necessary, this disadvantage would be outweighed by a decrease of management costs (Van Brouwers-Haven and Lokker, 2010). However, projects aimed at a top-down implementation of this strategy met with resistance from agricultural stakeholders. A lock-in situation developed, which raised awareness that more effective stakeholder collaboration was needed to produce legitimate results and develop viable management strategies.

To aid this resolve, various processes of participatory knowledge development have been instigated (van Brouwershaven and Lokker, 2010), a boundary organization for innovative peatland management was created and alternatives to a top-down mode of environmental governance were explored (den Uyl and Driessen, 2015). Nevertheless, at most locations, the soil subsidence rates have remained unsustainably high. Although it has been shown that innovative applications of field drains can reduce soil subsidence and improve the conditions for all stakeholders, this requires (a) a clear understanding of their site-specific impacts, and (b) consensus on a fair distribution of their costs among the stakeholders (van Hardeveld et al., 2018). These implementation challenges are not easily overcome, because site-specific collaborative management strategies to reduce soil subsidence have not become commonplace.

For this context, we developed RE:PEAT, an ISS for the collaborative management of peatlands which accurately assessed the site-specific impacts of management strategies and supported negotiation processes on goals, means, and implementation pathways. Next, we applied RE:PEAT in ten workshops, in which the participants faced the assignment of improving the future conditions of a specific site in the Dutch peatlands. All participants could influence the simulation by stakeholder-specific actions and transactions with other stakeholders. We used post-workshop questionnaires to enquire about the workshop participants' perceptions of the added values of RE:PEAT to overcome the aforementioned implementation challenges for collaborative management strategies. To reveal how the participants used RE:PEAT, we also enquired about their attitude and their strategies, and recorded the workshop proceedings on logfiles and video. In addition, we experimented with different workshop settings and analyzed how these settings influenced the outcomes of the workshops. The combined results of our experiment were used to derive an in-depth perspective on how ISS can improve the support of environmental management.

2.2. Developing RE:PEAT

Aided by several key experts on the Dutch peatlands, we developed an ISS for peatland management. The core of the ISS consisted of a spatially and temporally explicit modeling framework that simulates the interrelated dynamics of surface water levels, phreatic groundwater tables, and soil subsidence, as well as the ensuing effects on embankments and hydraulic structures, real estate, CO_2 emissions, and crop yield (van Hardeveld et al., 2017). Following the Cost-Benefit Analysis approach of van Hardeveld et al. (2018), we combined the modeling framework with empirical economic data, to simulate the investment sums and maintenance costs required for the water system, field drainage, real estate, gardens, and roads and sewers, as well as the Net Value Added of the agricultural production and the agricultural supply chain.

We combined the expanded modeling framework with the Tygron Geodesign Platform, an interactive software platform for accurate 3D modeling of spatial development projects (Warmerdam et al., 2006; Bekebrede et al., 2015). The combination with the Tygron Geodesign Platform transformed most scenario settings of the extended modeling framework, e.g., the drainage strategy or the land use, into actions that allowed users to influence the simulation. In addition, the Tygron Geodesign Platform allowed for monetary transactions during the simulation, as well as the levying of taxes.

As we wanted the resulting ISS to reflect the entire range of land uses in Dutch peatlands (i.e., dairy farming and other forms of agriculture, villages, and nature reserves), we expanded the ISS with several additional effects that we deemed relevant for these land uses. We used empirical data from water authorities so as to include the water supply required by drainage strategies, the amounts of dredged material (the numerous ditches and waterways in the Dutch landscape must be dredged regularly), and the amount of nutrients that drain to the water system due to soil subsidence and farm management. The water quality was included by comparing the simulated nutrient loads with threshold values for nutrient loads above which ditches become choked with duckweed. The threshold values were obtained by 1638 runs of the

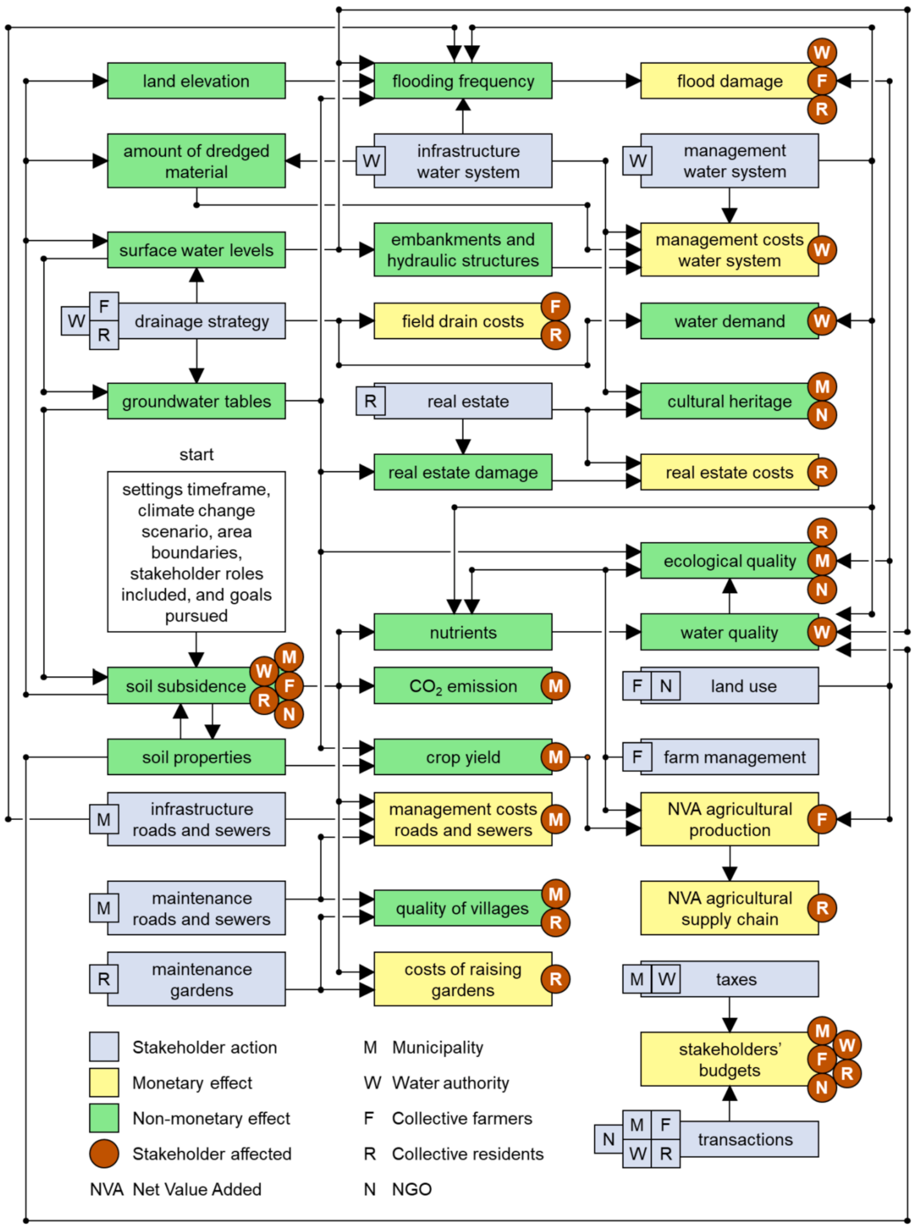

Fig. 1. Flowchart of the monetary and non-monetary effects simulated by RE:PEAT (adapted from van Hardeveld et al., 2018). Arrows indicate the sequence of the simulations. RE:PEAT includes five stakeholder roles that can simultaneously implement actions that influence the simulation. The squares indicate which stakeholders can implement an action. The circles indicate which stakeholders are affected by an effect. For all these effects, goals are set for improving the current situation. Throughout the simulation, the extent to which the goals are achieved is monitored.

PCDitch model (Janse and Van Puijenbroek, 1998), allowing for variations in (a) soil properties, (b) water depth, determined by the surface water level, and (c) water discharge.

Drawing on the approach of Sijtsma et al. (2011), we included an ecological quality score derived from land use and groundwater tables, which we extended to reflect the effects of water quality and farm management too. We also included scores for urban quality and cultural heritage, which we derived from stakeholder actions. For example, demolishing old real estate diminished the cultural heritage score, and increasing the maintenance of gardens increased the village quality score. Flooding was included by using raster-based rainfall-runoff computations based on the diffusive wave approximation (Horritt and Bates, 2001), which adequately compared with the analytical solutions of overland flow presented by Di Giammarco et al. (1998), with Nash-Sutcliffe efficiencies exceeding 0.99.

The resulting ISS, called RE:PEAT (an acronym derived from Platform for Evaluating and Anticipating Trends in peatlands), can be used iteratively to explore the myriad of options in collaborative environmental management. It is shown in Fig. 1. We included five stakeholder roles in RE:PEAT: (1) the municipality, which manages the infrastructure of roads and sewers, (2) the water authority, which manages the water system, (3) the collective farmers, who own most of the rural area, (4) the collective residents, who own most of the real estate in the villages, and (5) an NGO which manages the nature reserves. Note that in reality, farmers and residents predominantly operate individually. However, because their individual stakes were similar, for the sake of clarity and effectiveness, they were included collectively.

All stakeholder roles had a main individual goal and several accompanying goals: e.g., the main goal for the water authority was the reduction of management costs, with as accompanying goals the improvement of water quality and the reduction of water demand and

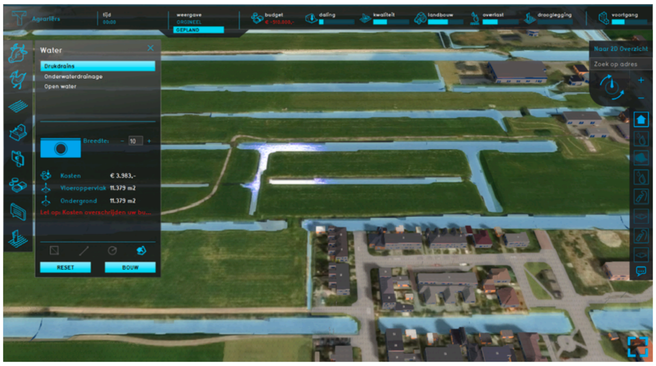

Fig. 2. Impression of the user interface of RE:PEAT. All users see the 3D simulation from their own perspective. The left bar contains possible actions, the right bar contains thematic maps, the top bar contains drop-down panels with information on goals, budgets, and a comparison of results with and without actions.

flood damage. In addition, all stakeholder roles shared the common goal of reducing soil subsidence. Several stakeholder roles shared accompanying goals as well: e.g., improving the quality of the villages was important for both the municipality and the collective residents. All stakeholder roles had a personalized graphical user interface available, which contained action menus, thematic maps, information panels, and a view on the 3D simulation from their own perspective (Fig. 2). The information panels showed their budgets and the extent to which their goals were reached. For all goals, the panels compared the results with and without actions. In addition, an overall information panel showed a graph of their progress score throughout the simulation. The progress score was derived from the main individual goal (40%), the accompanying individual goals (30%), and the common goal of reducing soil subsidence (30%).

2.3. Comparing workshops

We organized ten workshops in which we applied RE:PEAT (from March 10th till November 29th, 2016). The workshops were attended by a total of 89 participants, who were professionally involved in the management of Dutch peatlands. In addition, each workshop was attended by a facilitator, who oversaw the overall workshop process, and by 2–4 assistants, who could provide technical support if needed. All workshops alternated rounds of interactive simulation with plenary moments of instruction and reflection. The time spent on these activities varied (Table 1). In general, the workshops started with 30–90 min of plenary instruction, followed by two rounds of interactive simulation which both lasted 30–45 min. The rounds of interactive simulation were followed by plenary debriefings, which lasted 5–10 min after round one and 15–25 min after round two. Drawing from the guidelines for debriefing of Peters and Vissers (2004) and Kriz (2010), the debriefing between rounds focused on the perceptions of the participants, a joint reconstruction of what happened, and a discussion of further options for actions. The final debriefing addressed the connection between the simulation and reality, including speculation about hypothetical scenarios and exploration of pathways to put into practice the lessons that were learned. On several occasions we deviated from the general approach. For example, the participants in workshops 3 and 4 opted to spend more time on plenary instruction, at the expense of interactive simulation time. In workshop 10, the available time was relatively limited, so we economized on the time allocated to instruction by assigning a technical assistant to each stakeholder role, to help the participants operate RE:PEAT.

The settings of RE:PEAT reflected peatland areas of 9 km^2 and timeframes of 30–100 years, in which the gradual impacts of soil subsidence become apparent. For example, due to differences in soil subsidence rates, the differences in water levels between adjacent watercourses may increase. At some moment in time, this will require additional embankments to prevent the watercourses with higher water levels from slumping (van Hardeveld et al., 2017). The exact moment in time that the embankments are needed depends on the characteristics of the peatland area. The chosen timeframes were always sufficiently long to include the moment at which such impacts were manifested in the peatland areas that were considered. To accurately assess the soil subsidence rates throughout the considered timeframes, we took into account that the microbes that oxidize peat become more active when the temperature rises (Tate, 1987). Therefore, we gradually adjusted the soil subsidence assessment, to reflect a regional projection of 2 °C global temperature rise (van den Hurk et al., 2006).

We included 3–5 stakeholder roles. In workshop 1–9, each stakeholder role was allocated to pairs of workshop participants, who shared a laptop computer. Workshop 10 was an exception, with 5–6 participants per stakeholder role. In this workshop, the laptops were connected to large projection screens, to assure that all participants could see the user interface (Fig. 2) during the entire workshop. Due to the limited availability of hardware, the NGO was only included in workshops 1 and 2. In workshops 3 and 4, the participants requested omitting the collective residents, so as to focus more on the remaining three stakeholder roles.

To examine how RE:PEAT can improve the support of environmental management, we experimented with the settings regarding the style of the governmental roles and the involvement of the workshop participants (Table 1). We used two styles of the governmental roles to examine the effect of interventions that stimulate deliberation. In workshops 1–4, we allowed the municipality and the water authority to make top-down decisions, i.e., they did not require other stakeholder roles to consent to changing taxes and drainage strategies. These workshops allowed for a top-down implementation of drainage strategies, similar to what was considered at the turn of the century in the Dutch peatlands. For workshops 5–10 we changed this set-up, forcing the governmental stakeholders to deliberate their decisions, i.e., they

Table 1
Settings of the workshops.

Workshop no.	Time (hours:minutes)			No. of	Style of the governmental roles	Participant involvement
	Interactive simulation	Plenary	Total			
1	1:03	1:43	2:47	5	Top-down	Hands-on
2	1:06	1:50	2:56	5	Top-down	Hands-on
3	0:33	2:22	2:55	3	Top-down	Hands-on
4	0:33	2:22	2:55	3	Top-down	Hands-on
5	1:23	0:57	2:20	4	Deliberative	Hands-on
6	1:23	0:57	2:20	4	Deliberative	Hands-on
7	1:18	0:47	2:05	4	Deliberative	Hands-on
8	1:18	0:47	2:05	4	Deliberative	Hands-on
9	0:48	1:56	2:44	4	Deliberative	Hands-on
10	1:03	0:20	1:23	4	Deliberative	Guided

could only implement taxes and drainage strategies after obtaining the consent of the affected stakeholder roles. These workshops reflected the current ideas on peatland management, which acknowledge that cooperation between stakeholders is needed to produce viable management strategies.

We also experimented with the involvement of the workshop participants, to examine the effect of various application styles. Workshops 1–9 had a hands-on approach, with the participants operating RE:PEAT themselves. These workshops reflected a common setting of multiplayer serious game sessions, which had not been used before to support the management of the Dutch peatlands. Workshop 10 had a guided approach, with the technical assistants operating RE:PEAT on behalf of the participants. These workshops reflected a common setting of touch table sessions, which had been used on several occasions to support the management of the Dutch peatlands before our experiment (Arciniegas et al., 2013; Brouns et al., 2015). Overall, this resulted in three groups of workshops with different settings: (1) workshops 1–4 had a top-down government style and hands-on workshop participants, (2) workshops 5–9 had a deliberative governmental style and hands-on workshop participants, and (3) workshop 10 had a deliberative governmental style and guided workshop participants.

Because the workshops varied regarding the number of stakeholder roles and the duration of the interactive simulation (Table 1), we performed a sensitivity analysis. First, we analyzed the sensitivity of the results to excluding stakeholder roles that were not included in all workshops, i.e., the "collective residents" not included in workshops 3 and 4, and the "NGO" not included in workshops 3–10. Second, we analyzed the results' sensitivity to excluding workshops with less than 1 h allocated to interactive simulation, i.e., workshops 3, 4, and 9.

2.4. Perceiving added values

We used post-workshop questionnaires to enquire about the workshop participants' perception of the added value of RE:PEAT to overcome implementation challenges of site-specific collaborative management strategies to reduce soil subsidence. In particular, we enquired about (a) enhancing cooperation among them, and (b) increasing their understanding of problems and action perspectives regarding the peatlands. We used five-point Likert scales to measure their perceptions, ranging from −2 (very negative) to 2 (very positive). We used pairwise Mann-Whitney tests to assess statistical differences between the three groups of workshops.

In addition, we included an open question in the post-workshop questionnaires, enquiring about arguments to elucidate the perceptions of added values. Afterwards, we classified the 166 responses about the perceived added values into six categories. We derived categories 1–4 from Pelzer et al. (2014), who distinguished between added values of ISS on (1) the individual level, regarding learning about the nature of the planning object, (2) the individual level, regarding learning about the perspective of other stakeholders, (3) the group level, i.e., the improvement of collaboration, communication, consensus, and efficiency, and (4) the outcome level, i.e., better-informed decisions. In a follow-up study, Pelzer et al. (2016) found that participants in ISS workshops perceived the added values at individual level to be key. We therefore selected both individual values as separate categories. In addition, we included categories for (5) the context of the application, e.g., the characteristics of the participants, the policy process, and the political context (Geertman, 2006), and (6) the usability of RE:PEAT, e.g., transparency, user friendliness, calculation time, and integrality (Pelzer et al., 2016). We used Fisher's exact tests to assess statistical differences between the three groups of workshops.

2.5. Exploring different uses

To reveal how the workshop participants used RE:PEAT, we used logfiles that recorded all the actions of the stakeholder roles during the simulation. In addition, we used multiple video cameras to capture the activities of the actual workshop participants too. Afterwards, we synchronized the videos and time-coded the activities of each workshop participant. Drawing on the system for coding group working relations developed by Nyerges et al. (2006), we used four codes to annotate the activities of the workshop participants: (1) inactive, e.g., checking a cell phone or pouring a glass of water, (2) reflective, i.e., (a) getting support from technical assistants, and (b) observing the interaction between other stakeholder roles, (3) interactive, i.e., discussion with other stakeholder roles, and (4) explorative, i.e., (a) focusing on the computer screen, and (b) discussion with participants within the same stakeholder role. For each participant, we logged the cumulative number of actions and interactions hour^{-1}, and the cumulative time spent on all coded activities. We also used the logfiles to examine to what extent the workshop participants reached their goals, and to what extent their own actions and the actions of other participants contributed to their overall progress score. We used pairwise Mann-Whitney tests to assess statistical differences between the groups of workshops. Regarding the time codes, we excluded the inactive episodes (time code 1), which on average accounted for 3.8% of the time.

We used post-workshop questionnaires to enquire about the participants' perception of their attitude. We used seven-point Likert scales to measure these perceptions, ranging from −3 (very uncooperative) to 3 (very cooperative). In addition, we included an open question, enquiring about the strategies they employed during the workshop. Afterwards, the 210 responses to the open question were grouped into five categories: (1) influencing the social system, e.g., brokering deals with other stakeholders, (2) influencing the physical system, e.g., implementing measures, (3) improving personal welfare, either by maximizing profits or by minimizing costs, (4) improving the peatlands, e.g., by minimizing the soil subsidence, and (5) no clear strategy. We used pairwise Mann-Whitney tests to assess statistical differences between the three groups of workshops regarding the attitudes of the workshop participants. To assess differences in their strategies, we used Fisher's exact tests.

3. Results

3.1. Differences in the perceived added values

In post-workshop questionnaires, the workshop participants clearly stated they perceived RE:PEAT to be of high added value for enhancing cooperation among them and increasing their understanding of the social–ecological system (Table 2). The perceptions of the groups were consistent, with only small differences between them. The proportion of workshop participants who elucidated their perceived added values with arguments regarding the outcome level was low; differences between the groups were not significant. Arguments regarding the added

Table 2
The average added values perceived by groups of workshop participants for enhancing cooperation and increasing understanding, and the proportions of the groups that used an argument to explain their perceptions. The scale of added values ranges from −2 (very negative) to 2 (very positive). Significantly different results ($p < 0.05$) between the workshops 1–4, 5–9, and 10 are denoted by the letters a, b, and c.

Workshop group	1–4	5–9	10	All
No. of participants	32	35	22	89
Added value for enhancing cooperation	1.3	1.3	1.5	1.3
Added value for increasing understanding	1.2	1.3	1.0	1.2
More awareness of other perspectives	38% [c]	60%	77% [a]	55%
Improved understanding of the peatlands	58% [c]	50% [c]	15% [a,b]	46%
Support to the group process	42%	33%	15%	33%
Better-informed decisions	8%	3%	0%	4%
Context of the application	65% [c]	57% [c]	8% [a,b]	51%
Usability of RE:PEAT	50%	37%	46%	43%

value at group level and individual level were more common. The argument "more awareness of other perspectives" was used by the largest proportion of workshop participants to explain their perception of the added values. The proportion using this argument differed significantly between the groups in workshops 1–4 and workshop 10 ($p = 0.037$). The group of workshop 10 also stood out regarding the proportion that used the argument "improved understanding of the peatlands": it was significantly lower than the proportions for the groups of workshops 1–4 ($p = 0.017$) and workshops 5–9 ($p = 0.045$).

Approximately half of the participants remarked that the added values strongly depend on the context of the application, such as the workshop setting and the characteristics of the participants. Some of them elucidated their remark by suggesting that the absence of conflicts was an important precondition for the added values. Their general perception was that although conflicts have not disappeared, there is a trend toward consensus and cooperation among the stakeholders in Dutch peatlands. Only for such contexts did they perceive high added values. Interestingly, the participants in workshop 10 seemed less troubled by such considerations: the proportion making such remarks was significantly smaller than in workshops 1–4 ($p = 0.006$) and workshops 5–9 ($p = 0.001$).

Almost half of the workshop participants mentioned that the usability of RE:PEAT contributed to their perception of the added values. Specifically, they mentioned the credible results, the abundance of detailed information, and the realistic visual quality of the user interface. For example, the impact of site-specific soil subsidence rates on the length of watercourses that required embankments to prevent them from slumping, or the impact of site-specific groundwater tables on the Net Value Added of dairy farms. Some of them acknowledged that in general they struggled to comprehend the full complexity of peatland management. They found RE:PEAT very useful because it presented a clear overview of all the aspects.

3.2. Behavioral differences during workshops

Logfiles and video recordings of the workshops revealed that on average, the workshop participants simulated 12.4 actions hour^{-1}, interacted with other participants 30.4 times hour^{-1}, and spent most of their time on exploration (Table 3). Per individual, the number of actions and interactions hour^{-1} differed markedly, with ranges of 2–38 actions hour^{-1} and 6–74 interactions with other participants hour^{-1} (Fig. 3). The average ratio of actions hour^{-1} to interactions hour^{-1} was 0.6, with only 16% of the participants exhibiting ratios greater than 1.0, i.e., engaging in more actions hour^{-1}. How the individual participants spent their time in the workshop also differed markedly, with ranges of 4–65% for time spent on reflection, 16–79% for time spent on exploration, and 5–52% on time spent interacting with other participants (Fig. 4).

To some extent, the variety in the behavior of the workshop participants related to the workshop settings. The participants in workshop 10 spent much time on dialog within their group with the technical assistants assigned to their stakeholder role. Therefore, they embarked on relatively few actions and interactions hour^{-1}. Consequently, their results differed statistically from both other workshop groups in terms of their average proportion of time spent on reflection (workshops 1–4 group: $U = 17.0$, $p = 0.000$; workshops 5–9 group: $U = 24.0$, $p = 0.000$), their average proportion of time spent on exploration (workshops 1–4 group: $U = 75.0$, $p = 0.000$; workshops 5–9 group: $U = 87.0$, $p = 0.000$), their average proportion of time spent on interaction (workshops 1–4 group: $U = 192.0$, $p = 0.005$; workshops 5–9 group: $U = 144.0$, $p = 0.000$), and their average number of actions hour^{-1} (workshops 1–4 group: $U = 84.0$, $p = 0.003$; workshops 5–9 group: $U = 31.0$, $p = 0.000$).

Table 3
The average number of actions and interactions hour^{-1} by groups of workshop participants, and their average proportion of active time spent on exploration, on reflection, and on interaction. Significantly different results ($p < 0.05$) between workshops 1–4, 5–9, and 10 are denoted by the letters a, b, and c.

Workshop group	1–4	5–9	10	All
No. of participants	32	35	22	89
Actions hour^{-1}	17.3 ^{b,c}	12.8 ^{a,c}	4.9 ^{a,b}	12.4
Interactions hour^{-1}	25.9 ^{b}	40.4 ^{a,c}	20.9 ^{b}	30.4
Time spent on reflection	19% ^{c}	19% ^{c}	48% ^{a,b}	26%
Time spent on exploration	52% ^{c}	47% ^{c}	32% ^{a,b}	45%
Time spent on interaction	29% ^{c}	34% ^{c}	20% ^{a,b}	29%

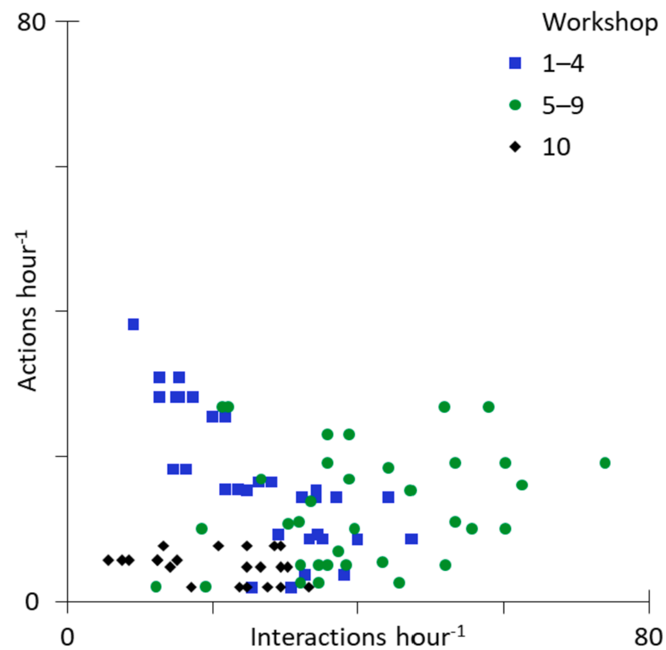

Fig. 3. The number of actions and interactions hour^{-1} of the workshop participants.

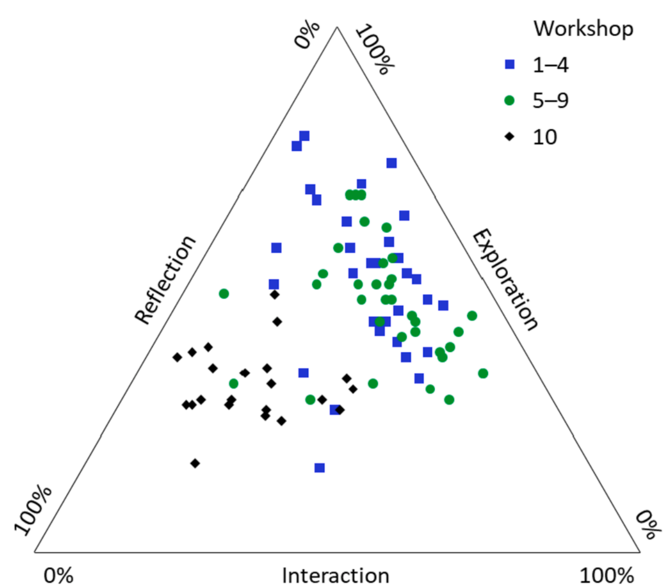

Fig. 4. The proportion of time spent by the workshop participants on reflection (left axis), exploration (right axis), and interaction (bottom axis).

Regarding the number of interactions hour^{-1}, workshops 5–9 were statistically different (workshops 1–4 group: $U = 233.0$, $p = 0.000$; workshop 10 group: $U = 80.0$, $p = 0.000$). The governmental decisions in workshops 1–4 did not require consent from other stakeholder roles.

Table 4
The average extent to which groups of workshop participants reached their goals, their average progress score, and the average extent to which their progress was caused by their own actions or the actions of other participants. Significantly different results ($p < 0.05$) between workshops 1–4, 5–9, and 10 are denoted by the letters a, b, and c.

Workshop group	1–4	5–9	10	All
No. of participants	32	35	22	89
Common goal: less soil subsidence	30%	46%	33%	38%
Individual goals	13%	17%	20%	16%
Overall progress score	18%	25%	26%	22%
Progress due to own actions	10%	4%	9%	7%
Progress due to actions of others	8% [b]	21% [a]	16%	15%

Consequently, compared with the participants in workshops 5–9, the participants in workshops 1–4 had fewer interactions hour^{-1} and more actions hour^{-1} (U = 258.0, p = 0.030). Although the governmental decisions in workshop 10 also required consent from other stakeholder roles, this did not result in markedly more interactions hour^{-1} than in workshops 1–4, because the participants in workshop 10 spent much time on discussions among the participants who shared their stakeholder role.

On average, the overall progress score during the workshops was 22% (Table 4). This may seem rather modest, but it must be noted that due to opposite effects of actions, high scores were very difficult to realize. For example, a raise in surface water levels would decrease the soil subsidence rate, which would increase the overall progress score. However, the frequency of flooding would increase as well, which would lower the overall progress score. Due to such opposite effects, only two pairs of workshop participants achieved an overall progress score of more than 50%. Remarkably, in workshops 5–10 the average progress was mainly caused by the actions of other participants, whereas in workshops 1–4 the progress was caused by the actions of the participants themselves. In this group of workshops, the progress due to the actions of other participants was significantly lower than in workshops 5–9 (U = 83.0, p = 0.014). The difference coincides with the significantly lower number of interactions hour^{-1} (Table 3).

Post-workshop questionnaires revealed that the participants used four types of strategies (Table 5), on average to almost the same extent. Significant differences were only found regarding the proportion of strategies aiming to influence the physical system: this was lower in workshop 10 than in workshops 1–4 (p = 0.008). The difference coincides with the significantly lower number of actions hour^{-1} (Table 3) and the significantly lower proportion of participants using "improved understanding of the peatlands" as an argument to explain their perception of added values (Table 2). It seems that the participants in workshop 10 focused more on the social system dynamics than on the physical system dynamics. Consequently, they might not have increased their understanding of the social–ecological system as comprehensively as the participants in the other workshops. However, their appreciation of the added value of RE:PEAT did not reflect this shortcoming, either because the effect was limited, or because they were unaware of it.

Table 5
The proportion of groups of workshop participants that employed a strategy, and their average attitude. The scale of attitude ranges from −3 (very uncooperative) to 3 (very cooperative). Significantly different results ($p < 0.05$) between workshops 1–4, 5–9, and 10 are denoted by the letters a, b, and c.

Workshop group	1–4	5–9	10	All
No. of participants	32	35	22	89
Influence the social system	52%	42%	41%	45%
Influence the physical system	76% [c]	39%	12% [a]	45%
Improve the personal welfare	32%	55%	35%	43%
Improve the peatlands	44%	33%	41%	39%
No strategy	4%	6%	12%	7%
Attitude	0.4 [b,c]	1.3 [a]	1.5 [a]	1.0

On comparing participants' attitude during the workshops, we found that for workshops 1–4, in which governmental stakeholders were able to enforce top-down decisions, scores were significantly lower than in workshops 5–9 (U = 268.0, p = 0.016) and workshop 10 (U = 109.5, p = 0.012), in which governmental stakeholders needed to deliberate their decisions with the other stakeholders. Note that on average, the lower scores did not reflect uncooperative impressions but impressions that were neutral to slightly cooperative. Uncooperative attitudes were only expressed by the participants in workshops 2–4. In these workshops, many participants behaved individualistically and exhibited ratios of actions hour^{-1} to interactions hour^{-1} of up to 4.2, i.e., strongly preferring individual actions over interaction and deliberated coordinated actions. Because in workshops 5–10 deliberation was mandatory for the governmental stakeholder roles, cooperative attitudes prevailed, with only one of the 67 participants expressing a slightly uncooperative attitude. It is noteworthy that participants in workshop 1 spontaneously engaged in several coordinated actions that required much deliberation, resulting in cooperative attitudes similar to workshops 5–10 (an average attitude score of 1.5).

3.3. Sensitivities analyzed

The sensitivity analysis (see Appendix) revealed only minor changes in the results, due to the exclusion of (a) the stakeholder roles that were not included in all workshops, i.e., "collective residents" and "NGO", and (b) the workshops with less than 1 h allocated to interactive simulations, i.e., workshops 3, 4, and 9. Any changes in statistically significant differences between groups of workshops primarily reflected the smaller group sizes resulting from the exclusions. We therefore deem the results not biased by variations in the workshop settings.

4. Discussion

4.1. System design

The system design of an ISS determines to what extent it can be used as a boundary object for the management of social–ecological systems. The general design principles are that the ISS should always promote communication and translation between experts, and promote mediation to avoid tradeoffs among the salience, credibility, and legitimacy of the scientific information (Cash et al., 2003). In our project, we aimed to secure these functions at the developmental stage of RE:PEAT by recruiting several key Dutch peatland experts to translate existing scientific knowledge into content that was salient from a stakeholder perspective, understandable by non-scientific participants, yet scientifically credible. Much of the knowledge incorporated in RE:PEAT resulted from preceding Science–Policy Interfaces, such as processes of participatory knowledge development (van Brouwershaven and Lokker, 2010) and a boundary organization for innovative peatland management. We believe the embeddedness of RE:PEAT in preceding Science–Policy Interfaces was an important condition for credibility and legitimacy. Arguably, without this embeddedness, the incorporated knowledge would have been more uncertain and disputable, which would have diminished the effectiveness of the ISS.

The workshop participants mentioned that the good usability of RE:PEAT also resulted from the abundance of detailed information and the realistic visual quality of the user interface. Arguably, these features enhanced the salience of the information for them. Throughout the simulation, they were continuously presented with sufficient information to make decisions, in an easily understandable format. The extent to which these ISS features can be enhanced is related to the resulting calculation times. An important condition for ISS is its ability to keep pace with stakeholder interactions during actual decision-making processes (Eijkelboom and Janssen, 2013; Leskens et al., 2014a). In our case, we were able to enhance the information load and the visual quality of RE:PEAT quite extensively, because the graphics processing unit was an integral part of its computing system. Therefore, the maximum calculation times were limited to a few seconds per action.

The ISS features that enhance its usability are strongly related to the main added values that were perceived by the workshop participants. Like Pelzer et al. (2016), we found that ISS workshop participants perceived the added values at individual and group level to be key, and the added value of a better-informed outcome to be less important. In the workshops, we witnessed how the participants collaboratively designed adaptive drainage strategies that could slow down soil subsidence. Although the generic effects of these adaptive drainage strategies had been known for approximately a decade (Querner et al., 2012), they had never been implemented on a large scale. Because RE:PEAT translated the generic scientific knowledge into site-specific effects from multiple stakeholder perspectives, it created an operational fit between knowledge supply and demand. In addition, because the RE:PEAT supported informed negotiations, it also raised awareness of mutually beneficial strategies. It is noteworthy that later, several workshop participants initiated a collaborative process to implement the adaptive drainage strategy designed during the workshops in the same peatland area they explored with RE:PEAT. Moreover, they intend to continue using RE:PEAT as a boundary object, to support collaborative management decisions in the years to come.

We believe the results show that the general purpose of ISS should reflect capacity building at the individual and group level, striving for a site-specific awareness of the effects of measures and strengthening the resolve of the stakeholders to collectively implement these measures. ISS applications should not primarily focus on better-informed outcomes. Although credible results are obviously important, the iterative and interactive exploration of the myriad of management options should be the key consideration in support systems for collaborative environmental management.

4.2. Workshop setting

Our experiment with different workshop settings revealed that all workshop participants explored the physical system dynamics, implementing measures, and the social system dynamics, brokering deals with other stakeholders. However, the participants in the workshops with a top-down government style implemented markedly more actions hour^{-1} than the participants in the other workshops. In addition, their strategies were primarily aimed at influencing the physical system, and their attitude during the workshops was significantly less cooperative than that of the participants in the other workshops. Consequently, they appeared not to have taken full advantage of the potential of RE:PEAT to enhance cooperation. Because of their focus on physical measures, their awareness of the perspectives of other stakeholders was markedly lower than the corresponding awareness in the other workshops. Furthermore, their overall progress was relatively limited, with other participants contributing significantly less to their overall progress than in the workshops 5–9. Our findings suggest that interventions that stimulate deliberation can prevent individualistic strategies, and instead foster cooperative attitudes. In our research, we achieved this by requiring mandatory deliberation of governmental decisions, which fostered cooperative attitudes in workshops 5–10. Other examples of interventions that can enhance cooperation are scripted instructions (Rummel and Spada, 2005), the incorporation of sequential phases with mandatory group tasks (Hämäläinen, 2011), and scripted collaboration with workshop participants (Papadopoulos et al., 2013) or their virtual counterparts (Hummel et al., 2011).

Our experiment with various application styles also produced some marked results. The participants in the guided workshop spent significantly more time on reflection than the hands-on participants in the other workshops. Consequently, they implemented markedly less actions hour^{-1}, and employed strategies that were less often aimed at influencing the physical system. In addition, in the post-workshop questionnaires, they claimed significantly less often that their understanding of the peatlands had improved. This might suggest that when the ISS application is primarily aimed at increasing the participants' understanding of the social–ecological system, a hands-on approach such as in multi-player serious gaming sessions is preferable to a guided approach such as in touch table sessions. However, we only regarded one workshop with a guided setting, which does not suffice to draw valid conclusions. Further research is needed to examine to what extent the results might have been caused by other factors, such as the limited time that was allocated to the plenary introduction and the debriefing in-between rounds. Furthermore, the impact of the facilitator and the technical assistants was underexposed in our research. The facilitator and technical assistants of workshop 10 had contributed to 5–9 previous workshops, in which they acquired the skills to effectively support an ISS workshop. Arguably, their performance contributed considerably to the added values that were perceived by the participants. Further research might increase our understanding of how ISS facilitators can help improve the support of environmental management.

4.3. Context

van Enst et al. (2014) identify two main contextual factors that define the “structuredness” of policy problems: consensus on relevant norms and values, and certainty about relevant knowledge. On the one hand, unstructured or “wicked” problems are deficient on both accounts. Therefore, they lack a definite solution and exhibit a range of strategical and operational science–policy interaction problems. On the other hand, completely structured problems are characterized by consensus as well as certainty, which makes science–policy interactions relatively straightforward. The context of Dutch peatlands can be seen as a moderately structured policy problem. Regarding knowledge, several Science–Policy Interfaces have increased the certainty of generic knowledge, but some uncertainty still remains, especially regarding site-specific effects from specific stakeholder perspectives. In addition, the workshop participants perceived a trend toward consensus among the stakeholders in Dutch peatlands.

For the workshop participants, the absence of conflicts was an important condition for the high added values they perceived. We therefore believe our results primarily demonstrate how ISS can be of added value for moderately structured environmental management problems. Arguably, ISS might be less effective in unstructured contexts, with less consensus on norms and values and less certainty about relevant knowledge. We suggest that in these contexts, efforts to support environmental management should primarily be aimed at Science–Policy Interfaces which are suited for such contexts, such as processes of participatory knowledge development, boundary organizations, and individual science–policy mediators (van Enst et al., 2014).

5. Conclusions

Our research demonstrated that ISS can improve the support of environmental management. Implementation challenges for collaborative management strategies can be overcome by translating generic scientific knowledge into site-specific effects from multiple stakeholder perspectives and by raising awareness of mutually beneficial strategies. In ISS workshops, all participants explored the physical system dynamics, implementing measures, and the social system dynamics, brokering deals with other stakeholders. As a result, the ISS workshops enhanced cooperation among them and increased their understanding of problems and action perspectives regarding the social–ecological system. Interventions that stimulate deliberation during the ISS workshops were shown to prevent individualistic strategies, and instead foster cooperative attitudes.

The embeddedness of an ISS in preceding Science–Policy Interfaces is an important condition for the ISS's credibility and legitimacy. Important conditions for the salience of the ISS are an abundance of detailed information, realistic visual quality of the user interface, and calculation times that are short enough to keep pace with stakeholder interactions during the decision-making processes. In addition, the general purpose of ISS should reflect capacity building at the individual and group level, striving for a site-specific awareness of the effects of measures and strengthening the resolve of the stakeholders to collectively implement these measures.

We suggest further research on interactive simulation systems should capitalize on the ability of our research approach to yield in-depth understanding of how ISS can improve environmental management. Cross-analyzing questionnaires with logfiles and videos of workshop proceedings can pinpoint how ISS can effectively harness science for complex environmental management tasks. This will help us understand how sustainable management of social–ecological systems can be put into practice.

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Appendix

Sensitivity analysis regarding the included stakeholder roles

Table A1
Changes in the results due to the exclusion of the stakeholder roles “collective residents” and “NGO”, in terms of the average added values perceived per group of workshop participants for enhancing cooperation and increasing understanding, and the proportion per workshop group that used an argument to explain their perceptions. The scale of added values ranges from −2 (very negative) to 2 (very positive). Changes in the significance of the differences between groups of workshops ($p < 0.05$) are asterisked. See Table 2 for the results that include all stakeholder roles.

Workshop group	1–4	5–9	10	All
No. of participants	24	26	16	66
Added value for enhancing cooperation	0.0 *	0.0 *	0.2 *	0.0
Added value for increasing understanding	0.0	0.0	−0.1	0.0
More awareness of other people's perspectives	6% *	−12% *	3% *	−2%
Improved understanding of the peatlands	−2% *	7% *	5% *	3%
Support of the group process	−3% *	−10%	−15% *	−9%
Better-informed decisions	−2%	1%	0%	0%
Context of the application	7%	10%	−8%	4%
Usability of RE:PEAT	11%	1%	−16%	1%

Table A2
Changes in the results due to the exclusion of the stakeholder roles “collective residents” and “NGO”, in terms of the average number of actions and interactions $hour^{-1}$ per group of workshop participants, and their average proportion of active time spent on exploration, reflection, and interaction. Changes in the significance of the differences between groups of workshops ($p < 0.05$) are asterisked. See Table 3 for the results that include all stakeholder roles.

Workshop group	1–4	5–9	10	All
No. of participants	24	26	16	66
Actions $hour^{-1}$	−0.3	0.8	−0.3	0.2
Interactions $hour^{-1}$	0.4	3.7	4.0	2.6
Time spent on reflection	−1%	−2%	−4%	−2%
Time spent on exploration	0%	−1%	1%	0%
Time spent on interaction	1% *	3%	3% *	2%

Table A3
Changes in the results due to the exclusion of the stakeholder roles “collective residents” and “NGO”, in terms of the average extent to which groups of workshop participants reached their goals, their average progress score, and the average extent to which their progress was caused by their own actions or the actions of other participants. Note that the significance of the differences between groups of workshops did not change. See Table 4 for the results that include all stakeholder roles.

Workshop group	1–4	5–9	10	All
No. of participants	24	26	16	66
Common goal: less soil subsidence	0%	0%	0%	0%
Individual goals	0%	−7%	−4%	−4%
Overall progress score	0%	−4%	−3%	−2%
Progress due to own actions	1%	−1%	−3%	0%
Progress due to actions of others	−1%	−3%	−2%	−2%

Table A4
Changes in the results after excluding the stakeholder roles "collective residents" and "NGO", in terms of the proportion per group of workshop participants that employed a strategy, and their average attitude. The scale of attitude ranges from −3 (very uncooperative) to 3 (very cooperative). Changes in the significance of the differences between groups of workshops ($p < 0.05$) are asterisked. See Table 5 for the results that include all stakeholder roles.

Workshop group	1–4	5–9	10	All
No. of participants	24	26	16	66
Influence the social system	−8%	−6%	9%	−4%
Influence the physical system	−4%	9% *	−12% *	0%
Improve the personal welfare	7%	−3%	15%	5%
Improve the peatlands	6%	3%	0%	3%
No strategy	2%	2%	−12%	−1%
Attitude	−0.1 *	0.0	0.3 *	0.0

We found only limited changes (Table A1–4). However, on several occasions, the limited changes in combination with the smaller group sizes affected the number of groups, yielding significantly different results. Regarding the added value for cooperation, the 4% increase in the average for group 10 resulted in significant differences (workshops 1–4: U = 38.0, p = 0.018; workshops 5–9: U = 44.0, p = 0.019). Regarding the argument "more awareness of other people's perspectives", the difference between workshops 1–4 and workshop 10 was no longer significant (p = 0.114), because a slightly larger proportion of participants in workshops 1–4 used this argument. A similar effect was found regarding the argument "improved understanding of the peatlands". A slightly larger proportion of participants in workshop 10 who used this argument rendered the difference with the other workshops statistically insignificant (workshops 1–4: p = 0.114; workshops 5–9: p = 0.054). An opposite effect was found regarding the argument "support of the group process". Because none of the remaining participants in workshop 10 used this argument, the difference between workshops 1–4 and workshop 10 was found to be statistically significant (p = 0.030).

Regarding the proportion of time spent on interaction, the averages of workshops 1–4 and workshop 10 became slightly more similar. As a consequence, for the smaller group sizes, the difference between workshops 1–4 and workshop 10 was not statistically significant (U = 57.0, p = 0.103). Regarding the proportion of workshop participants employing a certain strategy, we found that because the proportion of participants who employed strategies aimed at influencing the system was 9% higher in workshops 5–9 and 12% lower in workshop 10, the difference between these groups was statistically significant (p = 0.004). Although the changes regarding the attitudes and the impressions of interaction with other participants were also limited, they affected the number of groups with significantly different results. On the one hand, the average attitude of the participants in workshops 1–4 became slightly less cooperative, which was enough to prevent a significant difference vis-à-vis workshops 5–9 (U = 108.0, p = 0.128). On the other hand, the average attitude of the participants in workshop 10 became slightly more cooperative, resulting in a significant difference vis-à-vis workshops 5–9 (U = 36.0, p = 0.038). The average impression of the interaction was also more cooperative, which resulted in a significant difference vis-à-vis workshops 1–4 (U = 24.0, p = 0.010).

Sensitivity analysis regarding the duration of the interactive simulation

Table A5
Changes in the results after excluding short workshops, in terms of the average added values perceived per group of workshop participants for enhancing cooperation and increasing understanding, and the proportions of the groups that used an argument to explain their perceptions. The scale of added values ranges from −2 (very negative) to 2 (very positive). Changes in the significance of the differences between groups of workshops ($p < 0.05$) are asterisked. See Table 2 for the results that include all workshops.

Workshop group	1–4	5–9	10	All
No. of participants	20	25	22	67
Added value for enhancing cooperation	0.0	0.1	0.0	0.0
Added value for increasing understanding	0.0	0.0	0.0	0.0
More awareness of other people's perspectives	−3%	2%	0%	0%
Improved understanding of the peatlands	7%	−7% *	0% *	−2%
Support of the group process	8%	0%	0%	2%
Better-informed decisions	2%	1%	0%	1%
Context of the application	−5%	−9%	0%	−8%
Usability of RE:PEAT	−5%	11%	0%	3%

We found only limited changes (Tables A5–8). However, on four occasions, the limited changes in combination with the smaller group sizes affected the number of groups with significantly different results. First, the difference between workshops 5–9 and workshop 10 regarding the proportion of participants that used the arguments "improved understanding peatlands" was no longer significant (p = 0.140). Second, the proportion of workshop participants employing strategies aimed at influencing the physical system differed significantly between workshops 5–9 and workshop 10 (p = 0.028). Third, because the reduction of soil subsidence was less in workshops 1–4 and more in workshops 5–9, the difference between these groups was statistically significant (U = 40.0, p = 0.032). Fourth, the average attitude in workshops 1–4 was more cooperative. As a result, the difference vis-à-vis workshops 5–9 was no longer significant (U = 149.0, p = 0.342). This effect can be explained by the exclusion of the negative attitudes prevailing in workshops 3 and 4.

Table A6
Changes in the results after excluding short workshops, in terms of the average number of actions and interactions $hour^{-1}$ per group of workshop participants, and their average proportion of active time spent on exploration, reflection, and interaction. Note that the significance of the differences between groups of workshops did not change. See Table 3 for the results that include all workshops.

Workshop group	1–4	5–9	10	All
No. of participants	20	25	22	67
Actions $hour^{-1}$	0.7	3.0	0.0	0.4
Interactions $hour^{-1}$	1.5	1.6	0.0	0.3
Time spent on reflection	−1%	0%	0%	2%
Time spent on exploration	−1%	1%	0%	−1%
Time spent on interaction	1%	−1%	0%	−1%

Table A7
Changes in the results after excluding short workshops, in terms of the average extent to which groups of workshop participants reached their goals, their average progress score, and the average extent to which their progress was caused by their own actions or the actions of other participants. Note that the significance of the differences between groups of workshops did not change. See Table 4 for the results that include all workshops.

Workshop group	1–4	5–9	10	All
No. of participants	20	25	22	67
Common goal: less soil subsidence	−3% *	10% *	0%	5%
Individual goals	10%	2%	0%	4%
Overall progress score	6%	5%	0%	4%
Progress due to own actions	4%	1%	0%	1%
Progress due to actions of others	2%	3%	0%	4%

Table A8
Changes in the results after excluding short workshops, in terms of proportions of groups of workshop participants that employed a strategy, and their average attitude. The scale of attitude ranges from −3 (very uncooperative) to 3 (very cooperative). Changes in the significance of the differences between groups of workshops ($p < 0.05$) are asterisked. See Table 5 for the results that include all workshops.

Workshop group	1–4	5–9	10	All
No. of workshop participants	20	25	22	67
Influence the social system	1%	−3%	0%	−1%
Influence the physical system	3%	13% *	0% *	4%
Improve the personal welfare	10%	6%	0%	5%
Improve the peatlands	9%	10%	0%	7%
No strategy	1%	−6%	0%	−2%
Attitude	0.3 *	0.1 *	0.0	0.2

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