REVIEW

The negative effect of groundwater on *Sphagnum* (spp.) dominated bogs

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ABSTRACT
Previous research has looked into the effect of factors, such as the pH, water level, temperature, and nutrient concentration on peatland, separately. This paper looks at all factors, presenting a review of articles about the role of groundwater in peatlands, focusing on the negative effects of groundwater on *Sphagnum* (spp.) dominated bogs. Findings demonstrate that changes in water level, pH and calcium affect species composition, which can be seen as a negative effect. When defining a negative effect more strict, it can be concluded that only pH has a negative effect on *Sphagnum* dominated bogs, as findings suggest that high alkalinity led to rapid internal phosphate mobilization, peat disintegration and *Sphagnum* die-off. Die-off intensified with sulphate pollution. None of the articles really discussed groundwater in terms of origin, pathway, and related composition. In addition, the processes of acidification and methanogenesis are still not well known. Hopefully, this paper will encourage the inclusion of research on origin and pathway of groundwater, and on the different processes.

KEYWORDS · peatland · mire · bog · groundwater · surface water · *Sphagnum* (spp.) · ombrotrophy · hydrology · climate

INTRODUCTION

Peatlands, also known as mires, are important natural ecosystems with high value for biodiversity conservation, climate regulation and human welfare. Peatlands are wetland ecosystems that are characterized by the accumulation of organic matter (peat) derived from dead and decaying plant material under conditions of permanent water saturation. Together peatlands cover over four million km^2 in 180 countries (3% of the world's land area), accounting for at least a third of the global wetland resource and 30% of global soil carbon (Parish *et al*. 2008).

According to Breemen (1995), peatlands are usually classified as 1) bogs, which are fed by rainwater (ombrotrophic) and therefore poor in solutes and 2) fens, which are fed by groundwater (minerotrophic) and therefore usually richer in solutes from terrestrial sources, notably Ca^{2+}. Lamers *et al.* (1999), on the other hand, investigated raised bogs and did find that these may be affected by calcareous (bicarbonate-rich; HCO_3^-) groundwater, which is often found in deeper peat layers. It was also suggested that groundwater might provide an additional source of other nutrients (N, P and K). Others suggest that bogs are generally ombrotrophic, except when evapotranspiration exceeds precipitation. In that case, groundwater rises from the deeper peat towards the surface of the peatland (Glaser 1997; Fraser 2001).

Groundwater flow can have a profound effect on vegetation type (Glaser *et al.* in Devito *et al*. 1997), the pattern and dynamics of water chemistry (Siegel 1983; Hill and Siegel 1991; Branfireun *et al.* in Devito *et al*. 1997), exchange of atmospheric gases (Romanowicz *et al.* 1994) and metal transport (Hill and Siegel in Devito *et al.* 1997), depending on whether groundwater discharges to the surface of the peatland or water rechargers from the surface of the peatland into underlying aquifers.

Many plant genera, including *Sphagnum* (spp.) (peat moss), *Chamadaphne calyculata* (leather leaf), *Sarracenia purpurea* (northern pitcher plant), that grow in bogs are adapted to the low nutrient conditions present (Lamers 1999) and therefore vulnerable to changes in quantity and quality of their water supply (Erwin 2009).

This paper presents a review of the role of groundwater in peatlands, focusing on the negative effects of groundwater on *Sphagnum* (spp.) dominated bogs. Although previous research has looked into the effect of factors such as the pH (Hájková and Hájek 2004), water level (Hájková and Hájek 2004), temperature (Breeuwer *et al.* 2008) and nutrient concentration (Hájek *et al.* 2006), separately, the author was unable to find an overview.

The paper is constructed as follows. First, *Sphagnum* (spp.) dominated bogs will be described in more detail. Subsequently, the foremost theories on groundwater flow in relation to bogs will be shortly reviewed. This is followed by a presentation of findings concerning the influence of groundwater composition on *Sphagnum* resulting from the literature review. The factors that are considered are water level, pH, primary nutrients, temperature, calcium, and dissolved organic carbon (DOC). Lastly, the findings are brought together and knowledge gaps are identified.

THE GROWING CONDITIONS OF *SPHAGNUM* (SPP.)

The traditional view is that *Sphagnum* (spp.)[1] is well adapted to wet, nutrient poor circumstances (Moore and Bellamy in Breemen 1995). These circumstances are most prominent in ombrotrophic) peatlands, usually known as bogs or mires (Breemen 1995).

Bogs develop in a variety of ways often as a result of the infilling of lake sites by plant succession (Moore, 1997). The classical autogenic succession during the formation of a bog from a lake is: lake mud > *Phragmites* fen mud > *Alnus* fen > *Pinus/Betula* bog >*Scheuchzeria/Carex/Sphagnum* bog >*Sphagnum* bog (Breemen 1995). Many more pathways are possible, but most studied sequences end with communities dominated by the main peat forming vegetation *Sphagnum* (Breemen 1995; Moore 1997).

[1]*Sphagnum* (spp.) will from here onwards be indicated with *Sphagnum*.

Charman (in Hájkova and Hájek 2004) states that whereas the optimum of *Sphagnum* mosses is in moist and peat habitats, most other plants are stressed in this environment due to reducing conditions, nutrient insufficiency and mobilization of toxic metals. A general characteristic of bryophytes (including *Sphagnum*) is that they initially form a layer in close contact with the peat surface and react more flexible to a change in water chemistry and water level (Malmer *et al.* in Hájkova and Hájek 2004). Consequently, they have a competitive advantage for nutrient sources compared to vascular plants. Some claim that *Sphagnum's* own active role needs to be recognized in creating acidic, nutrient-poor, cold and anoxic peat in order to gain competitive advantage (Breemen 1995).

Another characteristic of *Sphagnum* is its water-holding capacity, which can be up to 20 times their dry weight (Moore 1997). This characteristic makes it possible for *Sphagnum* to grow to heights that are above the surrounding water table. Bogs are in this case indicated as 'raised bogs'.

HYDROLOGY

Over the years, several models have been proposed that try to give a satisfying explanation for the water flow path in peat structures. In 1978, Godwin described raised bogs as "huge flat sponges" that hold water against gravity by the forces of capillarity, although this model was not able to explain the in bogs observed high water table. Subsequently, Ivanov (1981) proposed the concept of a two-layered bog structure, on which Ingram (1982) based a model of a raised bog (in Moore 1997).

Rather than a simple sponge, Ingram described a raised bog as a hemisphere of solid rubber coated with a thin layer of sponge. In his model, known as the shallow-flow hypothesis, a thin layer of actively developing peat (the acrotelm) overlies the bulk of the peat mass (the catotelm) which is more compacted and is permanently saturated with water (Moore 1997). The acrotelm is 0.1-0.4 m thick, highly permeable, and dominated by lateral flow, while the catotelm is 0.5-6 m thick, slowly permeable and thereby, isolating the acrotelm from the mineral soil or bedrock (Breemen 1995; Reeve *et al*., 2000). It follows that in this case bogs are supplied with nutrients only by precipitation, because they are depicted as topographically high areas that are isolated from runoff and groundwater. However, according to Moore (1997), raised bogs can also be found in continental areas subject to relatively low precipitation, which places some question marks with regard to whether the shallow-flow hypothesis is correct.

Another hypothesis that exists is the groundwater flow hypothesis. This hypothesis assumes that water derived from precipitation moves downward under the bog dome flushing solutes from the deeper bog peat (Reeve *et al.* 2000). This is in line with the findings from Lamers *et al.* (1999), mentioned in the introduction. The groundwater flow hypothesis will be discussed in more detail in the next paragraph.

The groundwater flow hypothesis

A study of Romanowicz *et al.* (1994) has shown that the interconnection between local and regional groundwater flow systems and peatlands can be complex and result in significant groundwater movement. Furthermore groundwater flow can alternate between recharge and discharge patterns (Devito *et al.* 1997). With a recharge pattern, head gradients produce a flow from the surface of the peatland to the deeper peat, while with a discharge pattern, head gradients indicate that the flow goes from the deeper peat towards the surface of the peatland.

Glaser *et al.* (1997) discovered that raised bogs are mainly situated in regions in which groundwater flow changes direction depending on the amount of precipitation. Consequently, the raised bog system is able to maintain a slightly higher water table in dry periods due to the upward movement of water. Such flow reversals can be sustained on seasonal tot yearly time-scales and dramatically alter peatland biogeochemical functions (Romanowicz *et al.* 1994).

Fraser *et al.* (2001) looked at transient groundwater flow patterns in relation to different cation concentrations. To understand flow reversals they made geochemical profiles of Sodium (Na^{+}), Magnesium (Mg^{2+}) and Calcium (Ca^{2+}) concentrations in a bog. They also measured electrical conductivity on surface water, groundwater and precipitation. It was found that the highest cation concentrations correspond to the deepest measurements in de peat and vice-versa, indicating that profiles are the result of upward diffusion and mixing with meteoric water of low concentration.

Ferone (2001) writes that examining the solute concentrations of potential source waters confirms the importance of the shallow groundwater discharge to the pond chemistry. In the research of Ferone and Devito (2002) this influence of shallow groundwater on the pond water signature, despite its small volume, is inferred from the Ca^{2+} budgets. They concluded that Ca^{2+} concentrations in the shallow peat pore-water may reflect runoff and/or lateral groundwater flow inputs from the surrounding uplands during wet periods in the past, when the hill slopes could have contributed water to the peatlands.

THE INFLUENCE OF GROUNDWATER COMPOSITION ON *SPHAGNUM*

Following the groundwater flow hypothesis, an overview of earlier findings concerning the influence of groundwater on *Sphagnum* dominated bogs is presented.

Waterlevel

In 2004, Hájková and Hájek investigated, among others, the importance of water regime in Western Carpathian mires. They found that it was an important factor for vegetation composition. Each of the most common *Sphagnum* species has appeared to have a distinct niche regarding the water level. Figure 1 shows a modeled response curve of several *Sphagnum* species, with *Sphagnum contortum* having its optimum in the wettest places (e.g. little springs and streams in the peat), and *Sphagnum rubellum* having its optimum in the driest places.

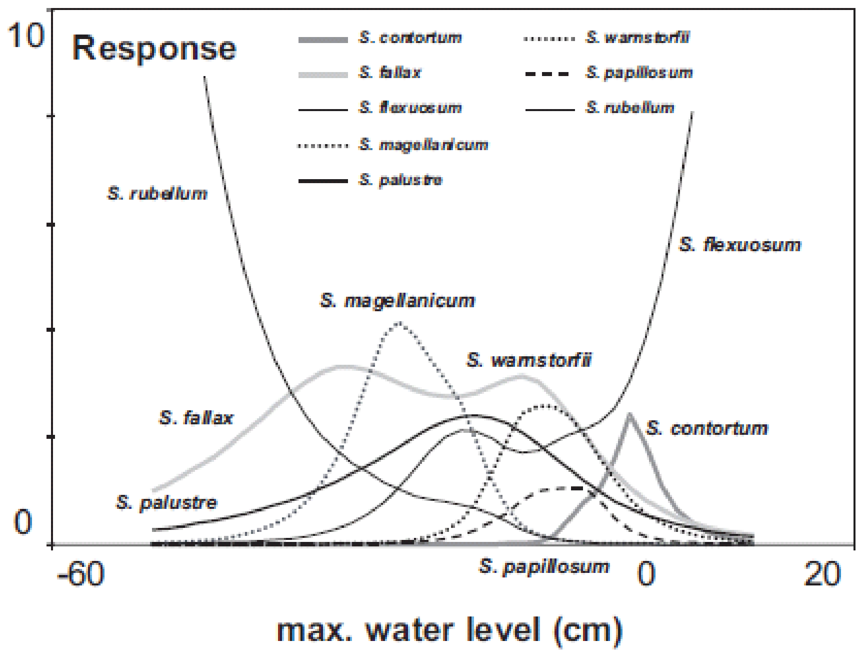

Figure 1 – The responses of the most common *Sphagnum* species to maximum water level gradient (only significant responses have been considered), modeled by the 'Generalized Additive Model' using a Poisson distribution. Reproduced from Hájková & Hájek (2004)

pH

Previous research has approached the pH and its influence on *Sphagnum* in different ways. On the one hand, research has focused on the kinds of *Sphagnum* species that are present under different pH values. On the other hand, research has looked at the effect of the addition of base rich groundwater on *Sphagnum*.

<u>pH and *Sphagnum* species</u>

Hájek *et al.* (2002) revealed a high correlation among the species composition of the vegetation and pH, conductivity, and mineral richness. Based on this research, in depth research was done to obtain a better understanding of water chemistry (Hájková and Hájek 2004). They found that the influence of water conductivity, pH and redox potential was just as an important factor for vegetation composition as water level.

It was shown that some of the investigated *Sphagnum* species had an optimum of groundwater pH, while others did not respond to groundwater pH at all. Figure 2 shows a modeled response curve of several *Sphagnum* species, with for example *Sphagnum warnstorfi* having its optimum around a pH of 6, and Sphagnum *fallax* finding its optimal conditions in the most acidic places.

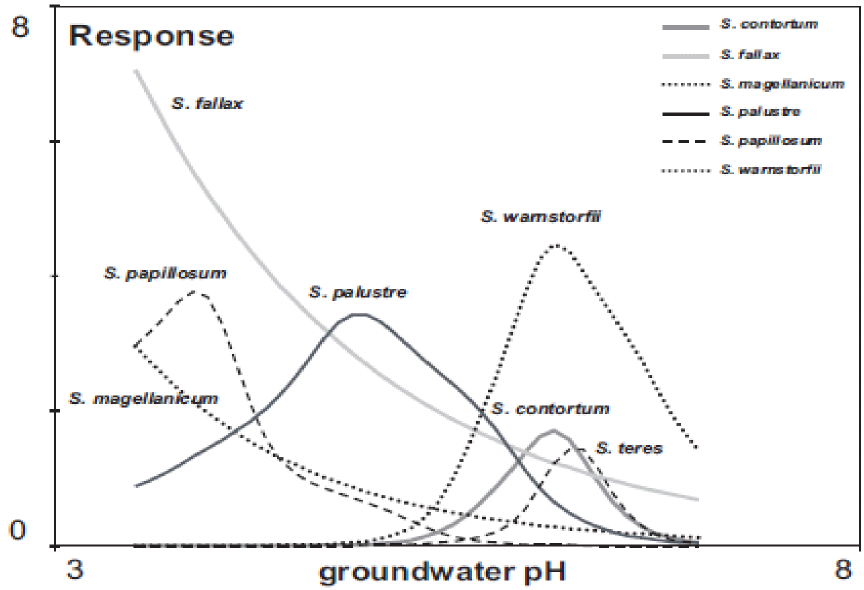

Figure 2 - The responses of the most common Sphagnum species to the groundwater pH gradient (only significant responses have been considered), modeled by the 'Generalized Additive Model' using a Poisson distribution. Reproduced from Hájková & Hájek (2004)

All in all, the figure shows that all *Sphagnum* species have their optimum within a pH range of 4 to 6. Hájková and Hájek (2004) furthermore note that a significant increase in the number of vascular plant species can be seen with increasing pH and conductivity.

pH and base rich water

The pH can be influenced by base-rich water, also known as buffered water. Buffered water originates from local groundwater flowing towards the peat base (Streefkerk *et al.* 1997 in Lamers *et al.* 1999). Lamers *et al.* (1999) mainly looked at the base bicarbonate (HCO_3^-), which originates from calcareous deposits in deeper layers and biogeochemical reduction processes. They investigated the effect of the influence of buffered (bi-carbonate rich) groundwater on the biogeochemistry and vegetation of bogs. In addition, the influence of sulphate (SO_4^{2-}) was researched, because nowadays, many peatlands are suffering from pollution from sulphate originating from the atmosphere, groundwater and/or surface water.

Their results showed that buffered groundwater and sulphate (SO_4^{2-}) pollution have an effect on the biogeochemistry and *Sphagnum* vegetation of bogs. They found that a slight increase in alkalinity stimulated buoyancy of living Sphagnum due to higher inorganic carbon concentrations in the water layer. Moderate alkalinity stimulated buoyancy as well, because of increased methane production (methanogenesis) rates.

High levels of alkalinity, however, led to rapid internal phosphate mobilization, peat disintegration and Sphagnum die-off. This effect was stronger when sulphate (SO_4^{2-}) was supplied simultaneously.

Primary nutrients

Nitrogen (N), phosphorus (P) and potassium (K) are the 3 primary nutrients for a plant. Nitrogen supports photosynthesis and is the primary building block for the leaves and stalks. Phosphorus stimulates root growth, maturation of seeds, and is needed for energy transfer and storage in plants. Potassium strengthens the resistance capability of the plant and stimulates the production of flowers and fruits. Lamers *et al.* (1999) suggest that groundwater might influence the balance by providing an additional source of the primary nutrients.

Increasing nutrients supply causes a resistance of *Sphagnum* species to high mineral levels (Kooijman and Kanne, 1993 in Hájek *et al.* 2006), resulting in a rise of *Sphagnum* productivity. Hájek and Hekera (2004) note that nutrient input is not always detectable in soil water, but is reflected by higher tissue concentrations of N, P and K especially at the community level.

Temperature

From literature it appeared that temperature influences nutrient concentration, and thus *Sphagnum* productivity. Hobbie (1996 in Breeuwer 2008) already said that it can be expected that increased temperature as a result of climate change will enhance decomposition rates in field situations, thereby increasing nutrient availability for both *Sphagnum* and vascular plants.

Breeuwer *et al.* (2008) investigated the influence of temperature further. They found that with an artificial increase in temperature, the nutrient concentrations (N, P and K) in *Sphagnum* were indeed higher. Moreover, N and K concentration increased compared to field values. Because in their research no nutrients were added with the rainwater solution, the higher availability of nutrients must have come from Sphagnum itself and the peat below. Probably the lower *Sphagnum* parts in the containers decomposed faster when the temperature was higher, making more N and K available for growth. Kalbitz *et al.* (2004 in Höll 2009) report a similar result as they found increasing dissolved organic carbon (DOC) production with increased microbial activity due to higher temperatures.

While temperature has a positive effect on decomposition rate, it thereby diminishes C sequestration in bogs (Hobbie 1996 in Breeuwer 2008).) It was furthermore noted, that particularly under field conditions, the potential response on temperature may not be realized in instances of competition from vascular plants, drought stress or extreme temperature increases (Breeuwer *et al.* 2008).

Calcium

Calcium concentration influences the *Sphagnum* vegetation, in the sense that when more Ca^{2+} is present, more Ca^{2+} tolerant *Sphagnum* species will be present in a bog. The activity of some Ca^{2+} tolerant *Sphagnum* species can lower the Ca^{2+} concentration in surface water, and lower the pH of surface water (Hájková and Hájek, 2004).

When there are no *Sphagnum* species that lower the Ca^{2+} concentrations, a high Ca^{2+} concentration is reached. Iron (Fe^{2+}), that is normally able to substitute at least partly for Ca^{2+} at the cation exchange sites in *Sphagnum* (Andrus 1986, in Hájková and Hájek, 2004), becomes unavailable for *Sphagnum* as cation exchange sites are filled with Ca^{2+} (Boyer and Wheeler, 1989; Bedford *et al.* 1999; Tyler, 2003 in Hájek *et al.* 2006). Vegetation may change to more iron-tolerant species of *Sphagnum* and many other plant species are restricted.

In addition, the continuous supply of even a small amount of Ca^{2+} in high-pH, iron-poor and infertile spring water maintains uninterrupted Ca^{2+} exchange on *Sphagnum* cell walls, and can therefore result in the same detrimental level of toxic Ca^{2+} in *Sphagnum* tissues as in more calcareous but stagnant water acidified by DOC (Hájek *et al.* 2006).

Dissolved Organic Carbon

Ferone and Devito (2002) measured dissolved organic carbon (DOC) concentrations. They found that although precipitation dominated the hydrologic inputs, the water chemistry of both ponds exhibited much higher concentrations of DOC than atmospheric water. According to Höll *et al.* (2009) DOC concentrations are related to seasonal variation, peat decomposition and C mineralization, with DOC concentrations being lower in winter then in summer. When peat decomposition is higher, DOC concentrations found in the soil solution and groundwater are also lower (Kalbitz *et al.* 2002, in Höll 2009). Results of Moore *et al.* (2008) imply a close, positive correlation between DOC production and C mineralization, depending on the composition of soil organic matter.

DISCUSSION

In the following section characteristics and findings about *Sphagnum* as given in the previous text are being discussed. Characteristics of *Sphagnum* are that it can handle reduced conditions, nutrient insufficiency and mobilization of toxic metals, which allows *Sphagnum* to be the main peat forming vegetation in bogs (Malmer *et al.* 1994, in Hájkova and Hájek, 2004). By some it is assumed that *Sphagnum* plays an active role in creating its own acidic, nutrient-poor environment in order to gain competitive advantage (Breemen 1995). However, not much research could be found that investigated this acidification process. Although *Sphagnum* may indeed have an active role in the acidification process, it can be questioned whether its goal really is to gain competitive advantage. It can be possible that *Sphagnum* only tries to gather all nutrients available because they live in a poor habitat, which by accident has acidification as a consequence.

Another characteristic of *Sphagnum* is that is has a high water-holding capacity which makes it possible for *Sphagnum* to grow to heights that are above the surrounding water table (Moore 1997). Groundwater is able to reach raised, *Sphagnum* dominated bogs as there is groundwater movement in peatlands (Romanowicz *et al.* 1994; Devito *et al.* 1997; Glaser *et al*. 1997; Lamers *et al.* 1999). Recharge (from surface to deeper peat) and discharge (from deeper peat to surface) patterns are found, depended on seasonal and yearly time-scales.

The influence of pH, primary nutrients, temperature, calcium, and DOC, and the influence of groundwater level on *Sphagnum* were investigated. Findings suggest that water level (Hájková and Hájek, 2004), pH (Hájek *et al.* 2002; Hájková and Hájek, 2004) and calcium concentrations (Hájková and Hájek, 2004) have an effect on species composition. PH also seems to have a positive correlation with the number of vascular plant species. In addition (Lamers *et al.* 1999), an increase in alkalinity stimulates buoyancy of *Sphagnum* until a certain level. High alkalinity led to rapid internal phosphate mobilization, peat disintegration and *Sphagnum* die-off. Die-off intensified with sulphate (SO_4^{2-}) pollution.

Increased primary nutrient supply (N, P, K) by groundwater flow seems to cause a resistance of *Sphagnum* species to high mineral levels (Kooijman and Kanne, 1993 in Hájek *et al.* 2006) and a rise in *Sphagnum* productivity. Temperature possibly amplifies this effect, as temperature rise was shown to cause a rise in nutrient concentration (Breeuwer *et al.* 2008).

Although all findings as named above are based on results found in bogs, bogs are location specific. In most of the articles the influence of groundwater is discussed through a change in one of the factors named above. In none of them groundwater flow is discussed in terms of origin, pathway and related composition. It can be expected that origin and pathway do matter, as composition might be affected when for example lateral flow brings in runoff water of higher situated areas. Different groundwater compositions may have different effects on *Sphagnum*. With groundwater flow not being defined, it might be that there are more factors that influence *Sphagnum* through groundwater flow that are not mentioned in one of the articles.

Not only can it be questioned whether there are more factors that influence *Sphagnum* through groundwater flow, but also it cannot be taken for credit that all factors that are found play a role in every bog. Findings as named above are the result of research done at different *Sphagnum* species. This review takes results as a whole, as not all articles specifically mention which result they found for which *Sphagnum* species. Depended on groundwater composition and *Sphagnum* composition, each bog will react differently on groundwater flow.

CONCLUSION

When defining the negative effects of groundwater on *Sphagnum* (spp.) dominated bogs, the term negative is debatable. When a negative effect is any change in niche and species composition it can be concluded that water level, pH and calcium all have a negative effect on *Sphagnum* dominated bogs. Temperature and nutrient level mainly have a positive effect on *Sphagnum* as they stimulate growth.

Defining a negative effect by *Sphagnum* being harmed, water level drops out as a negative effect, as only with increasing pH or with a continuous supply of calcium detrimental levels for *Sphagnum* are reached. In addition, with increasing pH an increase in vascular plant species can be found, which can be seen as negative as competition rises.

When a negative effect is defined by *Sphagnum* die-off it can be concluded that only pH has a negative effect on *Sphagnum* dominated bogs, as findings suggest that high alkalinity led to rapid internal phosphate mobilization, peat disintegration and *Sphagnum* die-off. Die-off intensified with sulphate pollution.

RECOMMENDATIONS

Different studies have investigated the influence of groundwater on peatlands. However, in none of them groundwater flow is discussed in terms of origin, pathway and related composition. In addition, the processes of acidification and methanogenesis, and their influences, are still not well known. Hopefully, this paper will encourage the inclusion of research on the origin and pathway of water, as well as more research on the processes just mentioned.

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