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A Dynamic Global Network Model of Earth's Health

Summary

In order to measure the Earth's health comprehensively, we built a dynamic global network model of Earth's health condition. We first examined the existing models and make some improvements. We identified nine key factors (Nodes) which have significant impact on the earth's health and found the connections among those Nodes. We used three measures to analyze Earth's health：species diversity , pollution spread and climate change. Finally we built a qualitative global dynamic network model of the Earth' health.

We build three quantitative models for three measures. To study and predict the climate change，we used a discrete probability model to simulate the circulation of CO_2 *in forest, marine system and urban area. To study the pollution spread over the nodes, we used the differential equation to model the nitrogen circulating and found the probability the spread. This model is also used for analyzing the impact of the areas of forest and cultivated land on the amount of species. To study the species diversity, we used a differential equation as a model for the quantity of species changing caused by the changes of areas forests and urban proportion. The same model was also used to predict to the changes of species diversity caused by the variety of one single species.*

We believe that those models connect the various factors and make the prediction of Earth's health condition by obtaining global tipping points, which enables decision makers to make more efficient actions in advance. However we realized we need more data to make those models more accurate and effective.

Our conclusions indicate that the most critical nodes of Earth's health are forests, urban, croplands and oceans. The health of the earth is reflected with the species diversity, pollution spread and climate change. The most influential factors on the Earth's health are CO_2 *emission, nutrients enrichment, pollutant discharge and urban expansion .*

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Introduction

Over the past 50 years, humans have changed ecosystems more rapidly and extensively than in any comparable period of time in human history, which has resulted in a substantial and largely irreversible loss in the diversity of life on Earth [Robert Watson et al.2005]. Many scientific studies have concluded that there is growing stress on Earth's environmental and biological systems, but these models ignore complex relationships among global factors and are unable to determine the long-range impacts of potential policies [Robert Watson et al.2005]. It’s important to build a dynamic global network model of some aspect of Earth's health by identifying local elements of this condition and appropriately connecting them to track relationship and attribute effects.

Our goal

- Identify the most simple and effective nodes that represent global system.
- Identify factors that could produce unhealthy global state-shifts
- Develop metrics to measure Earth's Health degree.
- Identify local elements of Earth's Health condition.
- Connect these elements to track relationship and attribute effects.
- Build global network models of the metrics to predict potential state changes of Earth's Health.

Our approach

- Analyze factors that can measure Earth's Health degree and connect the factors by the internal relation.
- Search the literature on existing evaluation methods and find their shortcomings.
- Develop a comprehensive evaluation method to Earth's Health.
- Search data to validate the efficacy of the model.
- Do a sensitivity analysis of variations of our model.
- Detail the strengths and weaknesses of the model.
- Predict tipping points in Earth's condition and inform decision makers on important policies.
- Do further discussion based on our work.

Analysis of representative Models

It's crucial to Earth's Health condition for human being. So we need to know how ecosystems have changed and predict state changes in Earth's condition. Scientists have made many studies in developing and using models to forecast the biological and environmental health conditions of our planet. Due to the different views of research, objects of study, methodologies and metrics, there're a series of models presented.

There are five representative models [Jacqueline Alder et al.2005]

The Asia-Pacific Integrated Model: Asia-Pacific Integrated Model is a large-scale computer simulation model. It assesses policy options for stabilizing global climate.

The IMPACT Model: IMPACT is an International Model for Policy Analysis of Agricultural Commodities and Trade. It has been applied to a wide variety of contexts for medium- and long-term policy analysis of global food markets.

The WaterGAP Model: The WaterGAP model is a principal instrument used for the global analysis of water withdrawals, availability and stress. It has been used in many national and international studies, including the World Water Assessment, the International Dialogue on Climate and Water.

Terrestrial Biodiversity Model: This model main focus on the analysis of species diversity and provides an overview of the different available methods to assess changes in biodiversity and their strengths and weaknesses.

Freshwater Biodiversity Model: This model is the relationship between the numbers of fish species to river size. Variations on this statistical model have been used successfully to predict current patterns of riverine fishes among rivers.

Weaknesses in current models

Ignore the relationships among different elements of Earth's Health condition.

Fail to predict potential state changes of Earth's Health condition.

Only restricted to local conditions and ignore complex global factors.

Unable to determine the long-range impacts of potential policies.

Our nodes

Local elements of Earth's health condition can be defined as networks nodes .Our *4* high level nodes are *terrestrial system, freshwater system, coastal system,* and *marine fisheries system.* Our *7* lower level nodes are *urban, forest and wood land, cropland, lakes, glaciers, rivers, underground water* (figure 1).

Different nodes are consisted by many aspects which occupy different weights. Nodes can be expounded as followed.

Terrestrial system

Terrestrial system changes can be mainly observed from *Forest and Woodland, Urban, Croplands.* Forest is an important component of habitats.

Forest and Woodland:

Forests diverse ecosystem services include the conservation of soil and water resources, positive influence on local climate, the mitigation of global climate change, the conservation of biological diversity, improvement of urban and peri-urban living conditions, the protection of natural and cultural heritage, subsistence resources for many rural and indigenous communities, the generation of employment, and recreational opportunities [Patrick Gonzalez et al.2005].Deforestation is the single most measured process of land cover change at a global scale [FAO 2001a; Achard et al. 2002; DeFries et al. 2002].

Urban:

Urban demographic and economic growth has been increasing pressures on ecosystem s globally.Urban development trends do pose serious problems with respect to ecosyst em services and human well-being Urban and industrialization could reflect human element [Xuemei Bai et al.2005].

Croplands:

Approximately 24% of Earth's terrestrial surface is occupied by cultivated systems. Cultivated areas continue to expand in some areas but are shrinking in others. Improved cultivation practices can conserve biodiversity in several ways [Poh Sze Choo et al.2005].Croplands reflect agriculture development. In addition, fertilizer and agricultural chemicals can lead to water pollution.

Freshwater system:

Freshwater is mainly existed in rivers, lakes, underground water and glaciers.

Global freshwater use is estimated to expand 10% in the past decade. These rates reflect population growth, economic development, and changes in water use efficiency. The supply of fresh water continues to be reduced by severe pollution from anthropogenic sources in many parts of the world. [Robert Bos et al.2005].

Coastal system:

Mangroves condition can stand for Coastal system.

Mangroves have a great capacity to absorb and adsorb heavy metals and other toxic substances in effluents. They can also exhibit high species diversity [Paul Dayton et al.2005].

Marine system:

Ocean is also an essential habitat for many species.
The lowered biomass and fragmented habitats resulting from over exploitation of marine resources is likely to lead to numerous extinctions, especially among large, long-lived, late-maturing species. Global catches increasing could lead to more abundant fish at lower trophic levels. [Andy Bakun et al.2005].

Our measures

Changes in ecosystem services are almost always caused by multiple interacting nodes mentioned above [Elena Bennett et al.2005]. So we need to find the internal connection of the nodes (building links) and devise measures of the earth health degree.

our measures are:

Amount of global species
Abundance of pollutant
The rate of temperature change.

Nodes connecting

Three most important direct drivers of change in ecosystem services are *species, pollution* and *climate change* [Robert Watson et al.2005]

CO_2 circulation and climate change

CO_2 in the air could reflect climate condition. Increasing carbon dioxide concentration has had more impact on historical radiative forcing on climate variability and changing than any other greenhouse gas [Richard Betts et al.2005].
Carbon dioxide is converted to carbohydrates by the process of *plant* photosynthesis. CO_2 is continuously exchanged between the atmosphere and the ocean; it dissolves in surface waters and is then transported into the deep ocean. Changeful CO_2 condition affects the species diversity immediately. [Richard Betts et al.2005].
Climate change is drived by greenhouse gas, especially CO_2 existing everywhere, and climate change impacts (e.g. sea level rise) are projected to have an increasing effect on biodiversity and ecosystem services. CO_2, a significant part of the global carbon cycle, has a fertilizing effect on most land plants and animals. With the development

of industry and agriculture,forest degradation can result in substantial carbon losses. CO_2 is continuously exchanged between the atmosphere and the ocean. Analyses of historical atmospheric CO_2 concentrations preserved in ice cores [Richard Betts et al.2005].

Pollution and nutrients spread

A model of pollution and nutrients spread will be introduced to connect *atmosphere*, *oceans*, *cropland*, *river* and *groundwater* in next section.
Pollution spread is mainly drived by nutrient cycle and water cycle.
The presence of nutrients such as phosphorus and nitrogen is necessary for biological systems, high levels of nutrient loading cause significant eutrophication of water bodies and contributes to high levels of nitrate in drinking water in some locations [Robert Watson et al.2005]. As the industrialization and croplands use continues to increase, *N* and *P* fertilizers will continue to play a dominant role in the global cycle. Nutrient spread by water cycle of rivers, lakes, underground water, coastal, oceans and the air sphere.

Biodiversity change

Species diversity is one of the levels of the biodiversity, Habitat change (land use change, water withdrawal from rivers, coastal change and ocean circulation).Habitat loss and other ecosystem changes are projected to lead to a decline in local diversity of native species in all four MA scenarios by 2050. [Elena Bennett et al.2005]

A model of biodiversity change will introduce to connect cropland, urban, and forest and explain how local habitat change influence *Species diversity*.

Summary and network

The most direct and effective links have been devised. CO_2 *circulation*, *pollutant and nutrients spread* and *biodiversity change*, then we can connect the nodes together to track relationship and attribute effects (Figure 1).

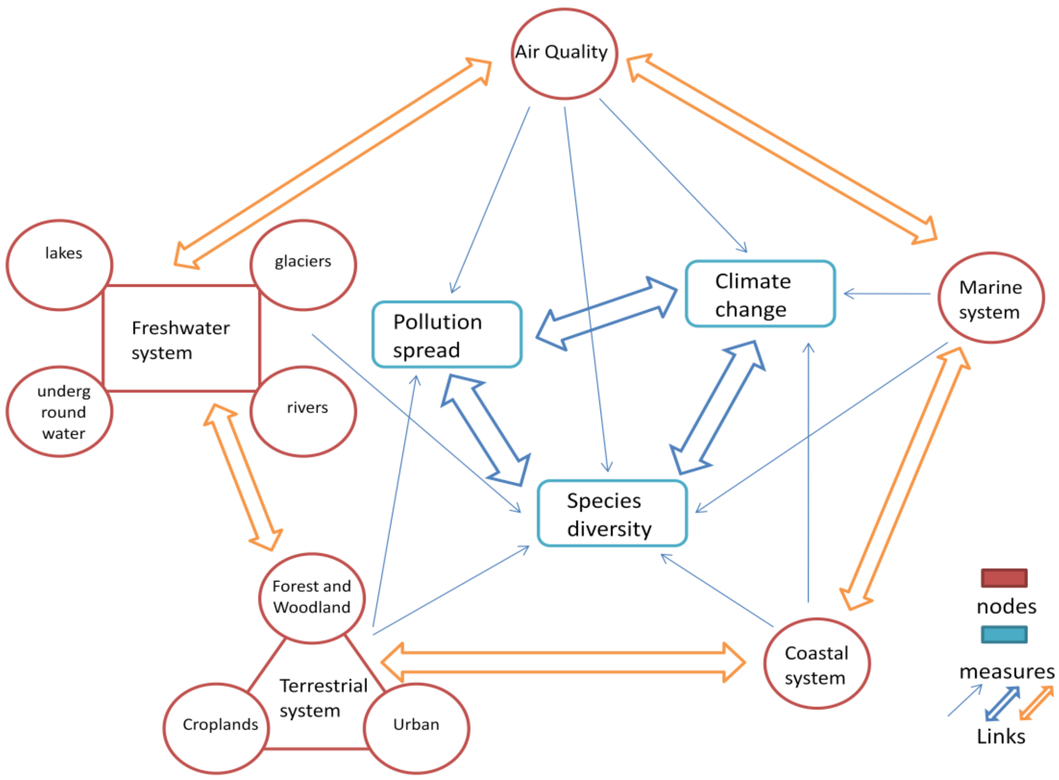


Figure 1 Network of the global model

Models of links

Network modeling for CO_2 circulating

CO_2 exists in the atmosphere and circulates in Local elements of the Earth. As the analysis above, CO_2 affect every node condition. So we need to ascertain CO_2 content in every node: Forest and Woodland, Urban, Croplands, Marine system and Freshwater, We formulate model using the Markov chain to account for calculating CO_2 content in every node , and forecasting variation trend of CO_2 [Frank R. Giordano, William Price Fox, 2009].

Methodology

We just use a discrete probability model for the CO_2 in the Forest, Marine system and Urban. Assume that every node could release and absorb CO_2, so with the changing of conditions, the probability of CO_2 circulating from one node to another have been known and defined as followed:

next state / currant state	Forest and Woodland	Marine system	Urban
Forest and Woodland	a_1	a_2	a_3
Marine system	b_1	b_2	b_3
Urban	c_1	c_2	c_2

Where ($a_1+ a_2+ a_3=1$, $b_1+b_2+b_3=1$, $c_1+c_2+c_3=1$, $0<a_1 ,a_2 ,a_3,b_1, b_2,b_3, c_1,c_2,c_3<1$)

We can get:

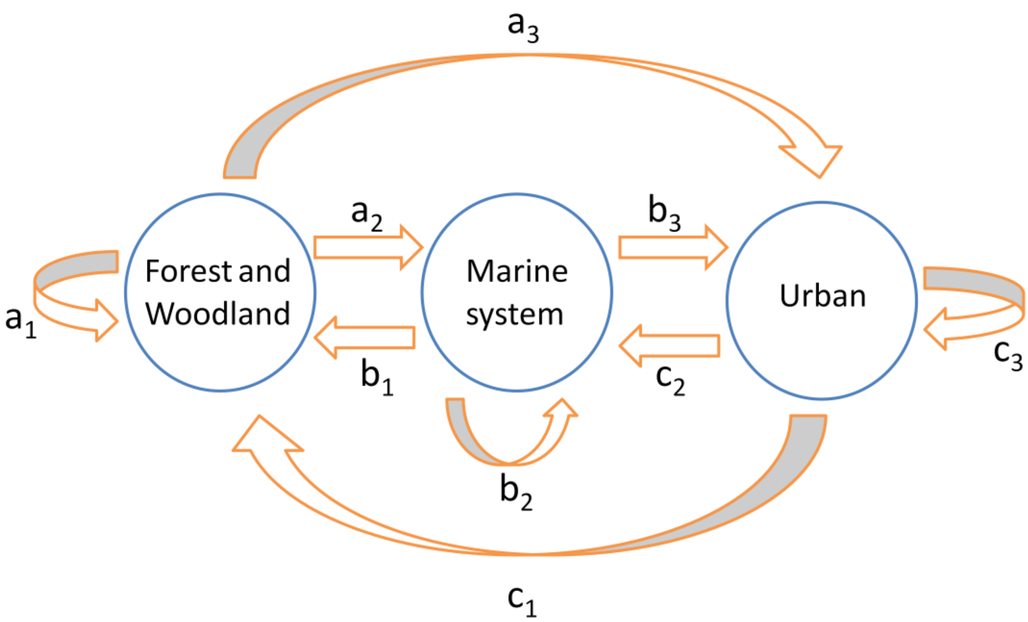


Figure 2 The *Markov chain* of the possibility of CO_2 circulating among three nodes

We define three variables:

A_n=The percentage of CO_2 content in the Forest and Woodland at moment called n ,

B_n=The percentage of CO_2 content in the Marine system at moment called n ,

C_n=The percentage of CO_2 content in the Urban at moment called n

Where (n=0,1,2,3,4,5……)

According to the variables defined above and concept of the Discrete Dynamical system [Frank R. Giordano, William Price Fox, 2009] .

We have equations set as followed:

$$\begin{cases} A_{n+1}=a_1A_n+b_1B_n+c_1C_n \\ B_{n+1}=a_2A_n+b_2B_n+c_2C_n \\ C_{n+1}=a_3A_n+b_3B_n+c_3C_n \end{cases}$$

Assume that, at first the percentage of CO_2 content in the Forest, Marine system and Urban is $\frac{1}{3}$ ($A_0=B_0=C_0=\frac{1}{3}$) .We can get the percentage of CO_2 content in the Forest, Marine system and Urban at every moment, then summarizing the variation tendency of CO_2 circulating. But we cannot get the probability of CO_2 circulating from one nodes to another (accurate data of a_1 ,a_2 ,a_3,b_1, b_2,b_3, c_1,c_2,c_3) , so the accurate tendency cannot be calculated.

Qualitative analysis for the CO_2 circulating.

The ability to release and absorb CO_2 is affected by distribution of plants, land use and absorbing of ocean. The probability of CO_2 circulating from one nodes to another also changes with the change of element mentioned above , which means a_1 ,a_2 ,a_3,b_1, b_2,b_3, c_1,c_2,c_3 are changing .

According to the analysis of the dynamic qualitative mode, we conclude with a series of recommendations for how best to control the amount of CO_2, thus we can understand climate change better.

This model can also be used to measure CO_2 circulating of the critical nodes remaining (Croplands, *rivers, lakes, underground water, glaciers, Mangroves and Marine system)*. Once the percentage of CO_2 content in any nodes change suddenly or verge to a stable value , which means the properties of the nodes has been changing , tipping point is coming.(e.g. When A_1 has been coming down suddenly , the other percentage must have changed rapidly . So the climate would change in the near future and vise versa.) Decision makers should pay attention to the tipping point, and take related measures to avoid the suddenly change of the climate.

Network modeling for the Pollution spread

According to analysis above, pollution spread in global. We can take the *N circulating* for example (Figure 4), to get a network model for the pollution spread.

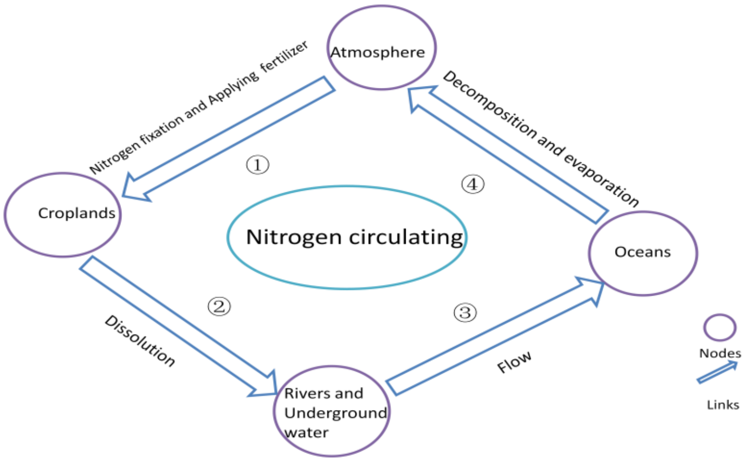


Figure 4 Process of Nitrogen circulating

According to the process of *Nitrogen circulating*, we can simplify this process to build a *differential equation* model for *Nitrogen circulating* [Frank R. Giordano, William Price Fox, 2009].

Take *Nitrogen* in Croplands, Rivers and Underground water and Oceans as pool, whose volume of the water in it at the moment t defined as $V(t)$.

Assume that, *N* flowing with water freely and spread uniformly. Water just inter the pool and then flow out of the pool without any other increasing or loss.

So define $p(t)$ = the gross of *N* in pool at the moment of *t*,

$c(t)$ =the concentration of N in the pool, $c(t) = \frac{p(t)}{V(t)}$,

We can get

In the interval of, $[\,t\,, t+\Delta t]$:

$\Delta p = p_{in} - p_{out}$, Δp is the variation of the gross of *N* in pool ,

p_{in} = the gross of *N* entering the pool,

$p_{in} = r_{in} c_{in} = \alpha \Delta t$,

r_{in} is the velocity of *N* entering the pool per litre ,

c_{in} is the constant gross of *N*,

α is a constant,

p_{out} = the gross of *N* getting out of the pool,

$p_{out} = r_{out} \frac{p}{V} \Delta t$,

r_{out} is the velocity of *N* getting out of the pool ,

So

$$\Delta p = \left(\alpha - \frac{p r_{out}}{V}\right) \Delta t \ ,$$

Make the limit of p at $\Delta t \to 0$,

$$\frac{dp}{dt} = \alpha - \frac{r_{out}}{V} p \ ,$$

When $V_0 = V(0)$, $V(t) = V_0 + (r_{in} - r_{out})t$,

$$\frac{dp}{dt} + \frac{p r_{out}}{V_0 + (r_{in} - r_{out})t} = \alpha \ .$$

The *Nitrogen circulating* in other critical nodes (Croplands, *rivers, lakes, underground water, glaciers, Mangroves and Marine system*) can also use this *first-order linear differential equation* to interpret.

Analysis of the Model

When $r_{in} \approx r_{out}$, *Nitrogen circulating* is balanced.

$r_{in} \gg r_{out}$, $\frac{r_{in}}{r_{out}} \to \infty$,

The tipping point appears. *Nitrogen* has been entering the pool at a high speed. We need to control the applying chemical fertilizer and pay attention to the *Nitrogen* from factories. Meanwhile we also need improve the species in lakes, rivers and oceans to enhance the ability to absorb *Nitrogen*.

$r_{in} \ll r_{out}$, $\frac{r_{in}}{r_{out}} \to 0$,

Another tipping point appears. *Nitrogen* to provide nutrient is at a low level and the balance is going to be broken. So we need to improve the croplands conditions and pay attention to the species diversity.

Network modeling for the Species diversity

Methodology to set measures:

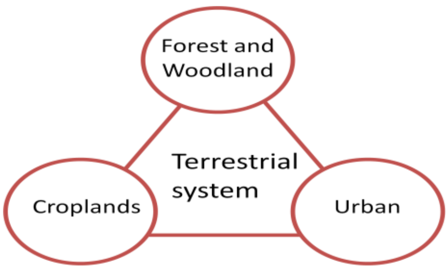
Our measures are *amount of global species, abundance of pollutant, and the rate of temperature change.*

Richness of animal i: $R_{ai} = \frac{number\ \ of\ animal\ \ i}{total\ \ catched\ animal\ \ in\ particular\ \ area\ (n)}$

Richness of plant i: $R_{pi} = \frac{area\ \ of\ plant\ \ i\ occupied}{area\ \ of\ animal\ \ habitat\ (froest\ \ ,cropland\ \ ,urban\ \ A\ )}$

Obviously R_{ai} and R_{pi} are range from 0 to 1.

:



partial network of terrestrial system

Relationship between the area of forest (*A*) and $\boldsymbol{P_{ai}}$(species number of animal *i*):

$$P_{ai} = c_i A^{z_i} \quad \text{(SAR)}$$

We can use data of R_i and A, paint picture of $log\,R_{ai}$ and $log\,A$ to set parameters. We assume diversity loss will occur as a result of the transformation forest into an urban or cropland, and then we can get:

$$P = kA_u^{\alpha}$$
$$A + A_u + A_c = constant$$

Where P is population of urban, A_u is area of urban, A_c is area of cropland, k,α are constants. We can use the same method to set parameters, thus we connect urban, forest and cropland.

animal connection

P_j is the amount of specie j such as a kind of animal, A is the area of habitat, M is environmental contain ability, r_j is constant, α_{ij} is transform coefficient defined as $\frac{dR_j}{dt} = \alpha_{ji}\frac{dR_i}{dt}$, it refers to one kind of animals change effect another kind of animal , P_a is total amount of animals in an area defined as $P_a = \sum_{i=1}^{n} P_{ai}$, n is amount of species,β is related to food web character defined as $\left(\beta = \sum_{i\neq j}^{n} \alpha_{ji} + 1\right)$.

According to logistic equation , assuming M is proportion to A, ρ is coefficient. we can get:

$$\frac{dP_{aj}}{dt} = r_j\left(1 - \frac{P_{aj}}{\rho A_j}\right) * R_{aj}\ .$$
$$\frac{dP_a}{dt} = \beta\frac{dP_{aj}}{dt}$$

We use last equation to predict how species j affects whole animal diversity.
Stable of animal j need:

$$1 - \frac{P_{aj}}{\rho A_j} = 0$$

Stable of animal food web need:

$$\beta = \left(\sum_{i\neq j}^{n} \alpha_{ji} + 1\right) = 0$$

Plant connection

Rank the species from the most competitors (species 1) to the poorest the equation for the species from the competitor for the dynamics of the ith species is

$$\frac{dR_{pi}}{dt} = c_i R_{pi}\left(1 - \sum_{j=1}^{i} R_{pj}\right) - m_i R_{pi} - \sum_{j=1}^{i-1} c_j R_{pj} R_{pi}$$

Where c is colonization rate, m is mortality rate. [David Tilman ,1994]
Assume due to human activity, cash tree dominate forest ecosystem and become high rank specie, we need to determine the appropriate cash tree colonization rate, and mortality rate. To get the tipping point we need:

$$R''_{plant\ differ\ from\ cash\ tree} = 0$$

Then we get a *2*(n-1) stable metrics* of appropriate cash tree colonization rate, and mortality rate. (*n* is number of species)
Besides and we need

Max (amount of animal)

Combine *model of animal in forest connect with each other* with *methodology to connect producer (plant) and consumer (animal),* we can get the most appropriate rate to plant cash tree from *stable metrics*.

Plant and animal connection:

As we know, animals eat plant, so we can use [Raymond N. Greenwell,1983] model to connect them:

$$\frac{dP_p}{dt} = r_p P_p\left(1 - \frac{R_p}{M_p}\right) - C P_a P_p$$

$$\frac{dP_a}{dt} = r_a P_a\left(1 - \frac{P_a}{\gamma P_p}\right)$$

Where P_p is quantity of plant, P_a is quantity of animal.
This method can be used to build dramatic model to predict biodiversity in marine system, coastal system and freshwater system. We can connect these nodes by CO_2 circulating, and Pollution spread.

Conclusion

- All the local elements of Earth's health condition are connected closely.
- The most critical nodes are *Forests, Urban, Croplands and Oceans*.
- The measures of Earth's health are *species diversity, pollution spread* and *climate change.*
- The three models can be used to predict the Earth's health condition.
- The most influential factors of the Earth's health condition are *CO_2 emission,*

nutrients enrichment, *pollutant discharge* and *urban expansion.*

Policies effection

Human related parameters are area of animal habitat (forest, grassland et al.), croplands or urban.
Assume one urban area develop very quickly, the city government's policy is to expanse city scale. According to equation 4, the population of city will increase then we need more crop- land.
So assume the area of urban and crop land increase by linear. Combine equations, we can get species of forest will decrease.

Global Tipping point

Symbols of global tipping points we have mentioned it before, are *Mass extinction* and *severe climate change*, so at tipping point *the rate of extinction* is maximum, *temperature change* is most severe critical nodes in our model are *urban*, *cropland*, and *forest*. Increase of croplands area will produce more nitrogen fertilizer. Through nitrogen circulation some creature will dominant freshwater or marine system, then the species of global will decrease. Increase of urban area will promote population growth so the area of forest will decrease the ability to absorb $CO_{2,}$ this will change temperature of earth; finally influence the abundance of species.

Strengths and weakness of the model

- Our system not limited to a certain point. Nodes of Earth's health condition are simple and effective.
- After combining all nodes in sequence. We get the relationships of nodes.
- the measures of Earth's Health degree are clear.
- The dynamic models can predict tipping points of Earth Inform decision makers on important policies in advance.
- The choice of the node is not complete and the relation of some nodes is undefined.

Advice to government

Our suggested solution, which is easy to implement, includes the statistics of species diversity, survey the extent of pollution and climate change trend. After analysising the measures, we can determine Earth's health.
Through the investigation in recent years, the earth is in the state of unhealthy. So the government should take measures as follows:

- Increase forests area.
- Build more natural reserves and pay attention to the species diversity.
- Reasonable planning factories.
- Reduce use of chemical fertilizer and control cultivated area within the effective range.
- Effectively treat pollution.
- Reduce the emission load of CO_2.

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