Hindawi Publishing Corporation
Applied and Environmental Soil Science
Volume 2015, Article ID 541818, 11 pages
http://dx.doi.org/10.1155/2015/541818

Review Article

Potential for Recycling Nutrients from Biosolids Amended with Clay and Lime in Coarse-Textured Water Repellence, Acidic Soils of Western Australia

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Received 27 September 2014; Accepted 29 December 2014

Academic Editor: Silvana Irene Torri

Application of biosolids in soils is an efficient method of recycling nutrients from biosolids and it is considered even safer when it is modified after mixing and diluting with other suitable soil organic amendments. A variety of soil organic amendments, such as green manures and composts, are used for modifying and co-composting with biosolids. However, these may not be considered as appropriate biosolids disposal and remedial measures for soils with unique problems such as low soil pH, water repellence nature, and poor water and nutrient retention capacities due to soil textural issues. Historically, soil amendments such as lime, clay, and recently biochar are being applied for such problematic soils at Western Australia and these researches focused mostly on improvement in soil physical and chemical properties. However, studies with potential for applying modified biosolids with these amendments are not complete yet. This review focused on identifying such gaps in these studies from over 170 peer-reviewed key research and review articles published over decades to latest in these areas.

1. Introduction

Coarse-textured, sandy soils are common in Mediterranean regions of Australia, which extend from Geraldton north of Perth, across south-western Australia and southern-south Australia, and into the Wimmera, Mallee, and northern districts of Victoria [1]. The Swan Coastal Plain on the coast of south-western Australia, within this Mediterranean environment, experiences hot dry summer and cool, wet winter with annual rainfall ranges between 500 and 600 mm [2]. Low fertility and soil nutrient deficiency are common in this climatic zone as the soils are derived from weathered, ancient rocks and are low in soil organic matter [1, 3]. Deep sand occurs at more than 80 cm depth and the pale deep sand found on the Swan Coastal Plain is typically classified as bleached-Orthic Tenosol [4]. Soil acidity, water repellence, poor water-holding, nutrient leaching, and environmental degradation are major issues that need improved soil management practices to increase productivity in the dry-land farming zones of this region [1, 5, 6].

Biosolids disposal is an international environmental issue as many developed countries are incinerating their biosolids or disposing them as landfills and ocean dumps [7]. Global production of biosolids exceeds 10 M t yr^{-1} and the production average is 27 kg of dry biosolids $person^{-1}$ $year^{-1}$ [8]. Several studies have focused on the advantage of recycling biosolids for beneficial agronomic effects on soil fertility from the organic matter and readily available and/or slow release plant nutrients available in the sludge [9–12]. Sludge addition usually increased plant growth both in field and in greenhouse experiments on different crop species [13–15]. On the contrary, research on the limitations of biosolids has demonstrated that excessively applied biosolids can release heavy metal and the metal accumulation and cause stress and restrictive effects on soil microbes [16–24] and on plant root and shoot biomass [25].

Other studies have focused on managing excessive N and P nutrient release from biosolids and risk for nearby surface water quality [26–29]. For instance, the Western Australian State of the Environment Report identified that eutrophication led to nearly 30% of accidental fish kills associated with excessive P and N leaching into waterways through fertiliser application (TN = 0.75 mg N L^{-1}, TP = 0.03 mg P L^{-1} trigger values indicated for the Swan-Canning estuaries as per guidelines of ANZECC and ARMCANZ) [30]. These studies show that no generalised application rate can be recommended; rather it is necessary to investigate sources of biosolids separately for a particular soil due to varying content of nutrients and metals present within biosolids [31–35].

1.1. Modified Biosolids Products. Traditionally, biosolids are applied to land in their original form for their nutritional value after treating raw sludge [15, 36, 37]. Plant nutrient imbalances as either deficiencies or phytotoxicities can occur when using these materials in unmodified forms [38]. This could outweigh the fertiliser value of sludge application. However, it is possible to rectify this problem by slightly modifying the physical and chemical properties of biosolids in addition to improving their formulation for safe disposal for specific soil conditions [38].

Several forms of modified biosolids are available for use in agriculture. The simple form of a biosolids mixture is lime-stabilised biosolids or LAB (lime-amended biosolids) [39, 40]. For example, a study conducted by Sloan and Basta [9] noticed that alkaline biosolids caused greater reductions in phytotoxic-Al when applied in strong acid soils than when applied with nonalkaline biosolids. In another study, Luo and Christie [39] found increased yield of barley when amending a mild to strong acid sandy loam (pH 4.5) soil with alkaline-stabilised biosolids at 33.5 t dry matter ha^{-1}. In this study, fly-ash, a liming material resulting from coal combustion, was used for alkaline stabilisation. The liming effect of the modified biosolids increased soil pH by about 1.2–1.5 units and as a consequence Al toxicity was reduced (from 4.0 to 0.1 cmol kg^{-1}) in barley crop that was grown under strong acid sandy soil conditions.

Manipulating soil pH using alkaline stabilised biosolids helped suppress the soilborne pathogenic nematode, *Meloidogyne incognita*, in addition to supplying plant nutrients in a loamy sand soil [41]. In this study, N-Viro soils, a commercial product developed by mixing biosolids with alkaline byproducts (such as coal ash, cement, and lime kiln dusts), was used as a soil amendment, further amended with urea fertiliser and kept for 5 days in incubation. It suppressed nematode growth which was directly associated with higher NH_3 production from urea and indirectly through increased soil pH by the alkaline biosolids.

Studies have also focused on mixing a variety of materials with biosolids to alter the nutrient or heavy metal availability that enhanced safe nutrient levels [42]. For example, there were benefits when biosolids were mixed with river sediments and/or composted with other organic materials such as oats straw and cattle manures [43–46]. A greenhouse study showed a significant increase in plant growth when soil was amended with a mixture of sediment and biosolids compared with application of either sediment or biosolids alone [44]. In this case, heavy metals were within an accepted range in the plant tissues when grown with the mixture. However, the impact on soil microbial communities was not assessed in this study. A formula that contains a mixture of biosolids with river-sediments was investigated for recycling nutrients from biosolids using native grasses [46]. It was suggested that mixing of biosolids with river sediments has potential benefit in increasing organic and inorganic nutrient content of the sediments and in improving sediment quality; the reclamation of damaged soils was improved at a field scale for the combination of biosolids and sediments compared with either sediment or biosolids alone. This study confirmed that a mixture of river sediment improved soil texture and increased plant available nutrients, microbial biomass, and plant growth. The mixture altered microbial community composition, with relative increases in Gram-negative bacteria and decreases in Gram-positive bacteria, fungi, and actinomycetes [46].

1.2. Research on LaBC in Western Australia. LaBC is a slow release organic amendment [47]. It is a typical modified clay and lime amended biosolids product (LaBC: lime-amended BioClay) formulated for use in acid sandy soils of the Swan Coastal Plain in Western Australia [47]. It has been demonstrated that LaBC has lower chemical contaminant threshold concentrations than that required for unrestricted use (C1 classification) based on Western Australian Biosolids Guidelines [47, 48]. This is a consequence of the severe dilution of the biosolids in a lime and clay blended product. LaBC has a number of desirable soil-organic amendment qualities such as improving water and nutrient retention capacity of coarse textured soils. It has been shown to alter soil pH ($CaCl_2$ extract) from 5.0 to pH of 8.0 as the product-blend is strongly alkaline (pH of 10.0) due to the presence of lime [48]. In addition, LaBC is rich in clay and organic matter and rich with significant amounts of plant nutrients from the biosolids component [48]. The clay material blended in the LaBC is not hydrophobic and has potential to reduce the severity of hydrophobicity of sandy soils when applied at rates greater than 50 tonnes per hectare [47–49].

The suitability of LaBC as a soil organic amendment has been investigated at both laboratory and field scales to evaluate the safe recycling of biosolids in the environment [48–52]. The chemical effects of LaBC in providing agronomical benefits for crop growth have been extensively demonstrated under both field and laboratory conditions [47, 48, 53]. Furthermore, field experiments have been initiated to investigate nutrient leaching risks after its applications and to study the long-term effect of LaBC using ryegrass [47, 50, 53]. However, the overall effect of LaBC on soil microbiological fertility was not considered in these studies and this requires investigation before the product is recommended for wide application in the soils of Ellen Brook catchment [54].

2. Major Problems in Sandy Soils and Their Causes

2.1. Soil Acidity. In south-western Australia, soil acidification is widespread and results in part from inefficient use of nitrogen in agriculture that enhances natural acidification processes [40, 47, 55]. Soil acidification from pasture and cropping affects about 3 M ha of cropped land in the Mediterranean region of Australia [56]. Soil acidity (mostly pH less than 5.5) commonly develops in agricultural lands in association with building-up of organic matter, frequent application of mineral fertilisers, and leaching of nitrate [55]. Acidity also creates Al and Mn toxicity to plants [9, 39, 57] and inhibits root nodulation and N-fixation in legumes [1, 58–61]. Low soil pH reduces the growth and activities of many soil microorganisms and this eventually leads to lower plant productivity due to decreased organic matter decomposition and mineralisation [62, 63]. Historically, agricultural lime or other liming materials are applied at rates of 1–1.5 $t\,ha^{-1}$ every 7–10 years in Australia based on soil buffering capacity and properties of liming materials, towards increasing soil pH for favourable plant productivity [40, 55, 64].

2.2. Soil Water Repellence. Soil water repellence develops by the accumulation of plant and fungi derived hydrophobic organic coating on the sand grains [6, 65, 66]. Soil organic materials, in particular stable humic fraction, have been identified as main reason for water repellence on sand grains [67–69]. Water repellence in soils of south-western Australia occurs mostly in coarse-textured sandy soils and sandy duplex soils that have less than 5% clay on the surface [1, 70, 71]. Water repellent soils have been investigated worldwide [67], for example, in USA, Florida and California, in New Zealand, and in Australia, and the involvement of organic matter is considered a factor associated with water repellence in all of these regions [67, 69]. In Australia, more than 5 million ha of land has been characterised with water repellent sands, including those on the Swan Coastal Plain [6, 72, 73]. Several studies also reported accumulation of wax-like long chain fatty acids of either fungal or plant origin and other similar types of organic compounds of plant origin, in particular, from *Eucalyptus* spp. as causes of water repellence [66, 74–76]. The nonwetting nature of soil increases the risk of water and wind erosion. Some 2 million ha of sandy soils across southern Australia is affected by wind erosion and leads to severe productivity losses [1, 6, 66, 77]. Nonuniform wetting of soil, often associated with nonwetting properties, results in severe yield reduction in agricultural land due to poor germination of seeds and less plant establishment in these regions [6, 66, 69, 78, 79].

2.3. Nutrient Leaching. Excessive fertilisation can accelerate nutrient leaching in sandy agricultural soils and has potential to cause environmental problems such as eutrophication [80], soil acidity [81], and ground water pollution [82, 83]. For instance, commercial bags of garden and all-purpose fertilisers should not contain more than 2% and 1% of P, respectively, according to the Environment Protection regulations guidelines of Western Australia. Nutrient retention capacity of sandy soils is generally very poor with excessive fertilisation in sandy soils increasing nutrient leaching [84] and free-draining sandy soils can threaten nearby water bodies.

For the Swan Coastal Plain in south-western Australia, nutrient leaching is a primary cause of ground water pollution [85, 86]. The contaminated groundwater further affects surface water quality of the river systems and surrounding lakes [87, 88]. Dissolved inorganic N and bioavailable P are generally the excessive nutrients that promote algal growth in water bodies [89–91] which can be hazardous to aquatic organisms and human health [92]. Maximum acceptable limit for nitrate in drinking water is 10 $mg\,L^{-1}$ according to World Health Organization. Hence, efficiency in application of nutrients should be the main objective in designing fertiliser plans for coarse-textured agricultural soils [86–88].

3. Potential Sandy Soil Management Using Amendments

3.1. Clay. Clay spreading is a sustainable and economically viable method for long-term remediation of water repellence in sandy soils [93] and claying is a common term used for top dressing transported clay materials on surface of the sandy soil, which is a practice used in south-western Australia. Increases in clay content of even 1-2% can play a crucial role in prevention of water repellence in a very sandy soil [70, 71]. Water repellence can be minimised by applying a higher amount of clay minerals (up to 100 $t\,ha^{-1}$) in sandy soils [70, 93, 94] and, in particular, use of kaolinite clay on a very severely water repellent soil has been shown as the best clay in overcoming water repellence [95]. Clay is attributed for its potential in increasing surface area that causes improved soil wettability [93, 95]. Conventionally, clay has been added at rates of 40–250 $t\,ha^{-1}$ on sandy soils in southern and south-western Australia to overcome the water repellence [70, 93, 94]. However, the technique of claying is continually being modified to attain maximum economic returns from degraded agricultural lands in various regions of Australia [6, 93].

3.2. Lime. Lime addition has been shown to decrease water repellence in sandy soils and liming is generally used as a common term for soil lime application [6, 69]. It has been demonstrated that lime added at rates of 3–15 $t\,ha^{-1}$ decreased water repellence under irrigated sandy soils in WA [6]. While liming is generally practiced to increase soil pH in acid soils, it has also been shown to increase microbial biomass and soil respiration that is associated with acid-intolerant microorganisms [62, 63, 96]. Increased soil microbial biomass and activities due to liming, in turn, increase mineralisation and nutrient availability for better plant productivity [63, 97]. However, increases in microbial activity, including mineralisation rates, are not consistent under different soil management systems [98, 99]. In a comparison of the practices of claying and liming, it was shown that lime applied up to 5 $t\,ha^{-1}$ could be used as an alternative for clay applied at 100 $t\,ha^{-1}$ in a sandy soil [6]. However, a combination of lime with clay was not included in this investigation. Furthermore, higher soil pH has been shown to increase the abundance of wax-degrading bacteria corresponding with a reduction in the hydrophobic layer that causes water repellence in sandy soil [6]. Therefore, management practices that decrease water repellence under acid soil conditions could be strategically planned by choosing a combination of soil ameliorants.

3.3. Biochar. Biochar is a byproduct resulting from pyrolysis (process of thermal degradation in the absence of air) of organic materials [100, 101]. Besides being popularly known for its carbon sequestration values [102–106], its soil ameliorating and agronomic values have equally attracted research attention worldwide [107–111]. Biochar characteristics differ (e.g., pH 6.2–9.9) with the various feedstock sources used under different production temperatures (260–700°C) [101]. There is no supply of direct plant nutrients available in biochar to help enriching soil fertility status [101, 112]. However, the varying micro- and macropore structures of biochar (from nano-, <0.9 nm, micro-, <2 nm, to macropores, >50 nm) [113] help increase soil surface area and retention of nutrients supplied through other fertiliser sources. These factors increase soil agronomic values and plant productivity in addition to providing a physical niche for beneficial soil microorganisms [101, 108, 114–116]. Therefore, biochar has potential for improving soil fertility by manipulating aspects of soil physical, chemical, and biological properties when amended with a range between 0.5 and 135 t ha^{-1} [101, 110, 117]. The nature of the manipulation depends on the origin of the biochar, as not all forms of biochar have the same characteristics [101].

The physical structure of biochar manipulates soil macro- and microporosity and provides microhabitat for soil microbial communities including fungi (arbuscular mycorrhizal (AM) fungi) and bacteria [108, 110, 118–120]. Management of microbial communities in agricultural soils depends on provision of soil conditions that suit their growth and activity [121]. Several studies have shown increased colonisation of AM fungi corresponding with biochar application [119, 122, 123]. The biochar particles buried in soil increased availability of micropore space which has been claimed to provide protective microhabitat for growth and extension of the hyphae of AM fungi into the biochar [124, 125]. The extended extraradical hyphae can thereby increase plant P uptake from soil [126–128]. Similarly, rhizobacterial activity and symbiotic nitrogen fixation with legume plants can be increased in association with biochar application [129]. Biochar applied to soil can protect rhizobia in pores <50 mm from predation in soils with low clay content and caused improved nitrogen fixation [130].

In addition to creating favourable microhabitat as a direct benefit to microbial communities, biochar application can help create favourable soil chemistry for their survival and plant uptake indirectly [124, 131–134]. For example, increased atmospheric N_2 fixation was observed in biochar-applied legume root nodules through improved symbiotic association with soilborne rhizobia [124, 129]. These effects are associated with a suppressive effect of soluble forms of N in soil solution on the N_2 fixation, while available soil P can provide supportive effect in the bacterial growth when soils are amended with biochar [118, 124, 135]. It has also been suggested that biochar may have a role in presence of fertilisers if they stimulate the available native strains of beneficial microbial communities in the soil [112, 132].

From an environmental perspective, soil amendment with some forms of biochar has potential to minimise nearby surface and ground water pollution [112, 136–141] through the mechanism of adsorption of dissolved organic carbon [119], NH_4^+ [112, 142, 143], and trace metals in leachates [144]. Soil amendment with biochar may also reduce heavy metal accumulation due to frequent applications of other organic amendments (e.g., biosolids) that contain potential metal contaminants [100]. Some studies have demonstrated increased bioavailability of plant nutrients and uptake of P, K, Ca, Zn, and Cu after charcoal application, while decreased N leaching has also been observed [112, 145–149]. A range of specific soil physical, chemical, or microbiological properties, therefore, may be manipulated by developing a careful soil amendment strategy with biochar, although not all biochars are expected to function in the same manner [110]. For instance, short-term negative impacts of biochars have also been attributed to volatile toxic organic compounds and phytotoxic salts that could have caused reduced microbial biomass C [143] and plant root growth activities, respectively [110].

3.4. Interactions between Clay, Biochar, and Biosolids. Characteristics of soil amendments are inherently different. They determine key roles in altering soil N mineralisation processes when applied independently or when coapplied with other amendments. While biosolids are usually considered as a source of nutrients (especially N) that accelerate N release into soil [150, 151], other amendments such as clay and biochar act as potential sinks and lead to retention of soil N and decrease N leaching into the immediate environment through various mechanisms [101, 110].

Dempster et al. [141] compared the efficiency of clay and biochar in achieving decreased N leaching in coarse-textured soils in south-western Australia. A lysimeter column study was investigated for 21 days after amending soil independently with 25 t ha^{-1} of clay and biochar with different application methods. Both amendments significantly decreased cumulative NH_4^+ leaching by about 20% and NO_3^- leaching by about 25%. However, biochar significantly decreased NO_3^- leaching more than clay did and this was mainly associated with a larger difference in anion retention capacity. While clay lacked the ability to retain NO_3^-, the biochar used in this study had a dual role in NO_3^- sorption processes and increased water holding capacity [141]. Moreover, the capacity of biochar to control N leaching in this case was associated with decreased nitrification values in amended soil as shown in a previous study [143].

Previous studies with biochar identified the same two important mechanisms as described above, which were attributed as potential reasons for decreased N leaching capacity. First the high NO_3^- retention was due to positive charge of biochar [152]. Second, decreased NH_4^+ leaching was due to improved gravimetric water holding capacity of soil rather than its sorption effect onto the biochar [112, 141, 142].

Coapplication of clay with other organic composts has been shown to be a beneficial soil management practice in coarse textured soils of south-western Australia and for similar environments [153]. As discussed above for the experiments of Dempster et al. [141], a preliminary 21-day study showed that clay also had a significant effect on decreasing N leaching in sandy soils and its effect was comparable with that of biochar. However, that study did not investigate whether the nutrients retained by clay or biochar were plant available or whether they helped increase the efficiency of use of fertiliser in the amended agricultural soil. Further, these studies did not investigate the combined effect of clay and biochar on plant growth nor did they investigate the combined influence on slow release fertiliser such as biosolids when they are coapplied in multiple combinations.

The inclusion of biochar helped decrease nitrate leaching from biosolids amended soils over five months [42]. A lysimeter column leaching study was established with ryegrass and amended with combinations of biochar (102 t ha^{-1} equivalent) and biosolids (600 and 1200 kg N ha^{-1} equivalent) in two types of silty loam soils. The inclusion of biochar and biosolids together resulted in significantly less nitrate leaching than in the biosolids alone treatment and suggested for higher rate application of the mixtures to rebuild degraded soils. However, developing an optimum mixture ratio and identification of the mechanisms responsible for alteration in the nitrogen cycle were not addressed in this study. There is potential that biosolids applied at a level equivalent to 1200 kg N ha^{-1} could become an additional risk associated with excessive leaching in conditions similar to those used by Knowles et al. [42].

The use of clay minerals such as Na-bentonite and Ca-bentonite could be a potential tool for immobilising up to 70% of bioavailable form of heavy metals such as Zn, Cd, Cu, and Ni in sewage sludge contaminated soil [154]. In an incubation study of more than 110 days, soil biological parameters such as microbial biomass C, respiration, and organic C mineralisation rate were higher in clay-amended soil, and this was associated with reduced heavy metal toxicity on the microbial parameters.

In comparison to the studies considered above, the combination of lime, clay, and biosolids makes LaBC a unique biosolids product with potential for benefits to be multiplied when coapplied with biochar. This raises scope of investigating the biosolids amendment in combination with other N-absorbing ameliorants [54].

4. Soil Microbial Properties

A shift in soil microbial communities can be associated with soil textural changes. For example, mineralization is influenced by soil texture and structure as they both affect the aeration status, the physical distribution of organic materials, and other physical, chemical, and biological environmental characteristics of soil [155–157]. Bach et al. [157] demonstrated that soil microbial community (using phospholipid fatty acid, PLFA method) responses to grassland restoration were moderated by soil texture during the monitoring of grassland ecosystem recovery for 19 years. Nevertheless, other studies have claimed that soil texture had no significant effect on the decomposition rate and/or microbial community structures when soils with contrasting textures were amended with carbon substrates such as low molecular weight carbon sources (e.g., glucose) [158–160]. However, addition of clay to soil could create new microhabitats, particularly if it has low clay content [161]. The added clay can contribute to an increase in soil microbial biomass [156, 162–164]. Despite conflicting observations, the respiration rate of preincubated soils could, at least to some extent, depend on the replacement of the labile substrate from soil organic matter, and the amount applied could decrease when soil texture is altered, for example, when texture is modified with increasing clay content [165].

Soil texture, in particular clay content, is an important factor which influences organic matter decomposition including the labile pool of carbon, that is, microbial biomass [166, 167]. Clay can physically protect living (microbial biomass C) and nonliving soil organic matter and causes reduced decomposition and CO_2 evolution in soils [165, 168, 169]. The direct physical protection of organic matter is possibly achieved by surface adsorption and entrapment of organic matter between clay layers and thereby prevents or reduces the rate of decomposition by soil microorganisms [170–173]. On the other hand, clay can protect the active component of living organic matter (known as soil microflora) by physically confining them in small pores, making them less active and protecting them against predation by soil protozoa [174]. Thus, clay is assumed to play a major role in minimising soil C mineralisation.

Umar [167] investigated the protective effect of clay minerals (5, 10, 20, and 40% w/w) on wheat residue (2% w/w) decomposition in commercial sand associated with decreased C mineralisation through 32-day incubation study. Clay applied at <20% decreased cumulative respiration until 28 days and this decreased C mineralisation was associated with a clay binding effect on organic matter. However, 20 and 40% clay increased the C mineralisation after 18 days which was associated with higher water retention capacity and corresponding increase in higher activities of microbial communities which were unable to survive in lighter-textured soils.

5. Conclusions

Biosolids disposal on soils with water repellent, acid, and coarse-textured characteristics will need to ensure that any nutrients from the modified product do not become a potential threat to the environment. While the potential agronomical influences of modified biosolids products use have been identified in terms of altering soil physical and chemical properties, their use in improving soil fertility with relevance to microbiological parameters has not been studied critically.

The potential benefits of combining biosolids with other amendments can include reduction in microbial processes such as mineralisation of organic matter. This could be beneficial if it led to slow release of nutrients from biosolids. There is a need for further investigation of the C and N mineralisation patterns and related changes in soil microbiological properties when combinations of clay, lime, and biosolids and/or biochar are applied to sandy soil. This information would enable greater understanding of how modified biosolids products influenced the short- and long-term dynamics of soil nutrient cycling following application to soil. It would clarify effects of plant rotation, in terms of the build-up of soil N, microbial biomass N, and bioavailability of N. Investigation of impacts on soil microbiological processes across the scales of laboratory incubation through a series of glasshouse and field experiments would contribute to modification of biosolids products to suit particular soils, plants, agricultural management systems, and environmental conditions.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

Sanjutha Shanmugam was awarded a Ph.D. Scholarship by The University of Western Australia with financial support of the Water Corporation of Western Australia. LaBC is a registered trademark product of the Water Corporation of Western Australia (WA, Australia).

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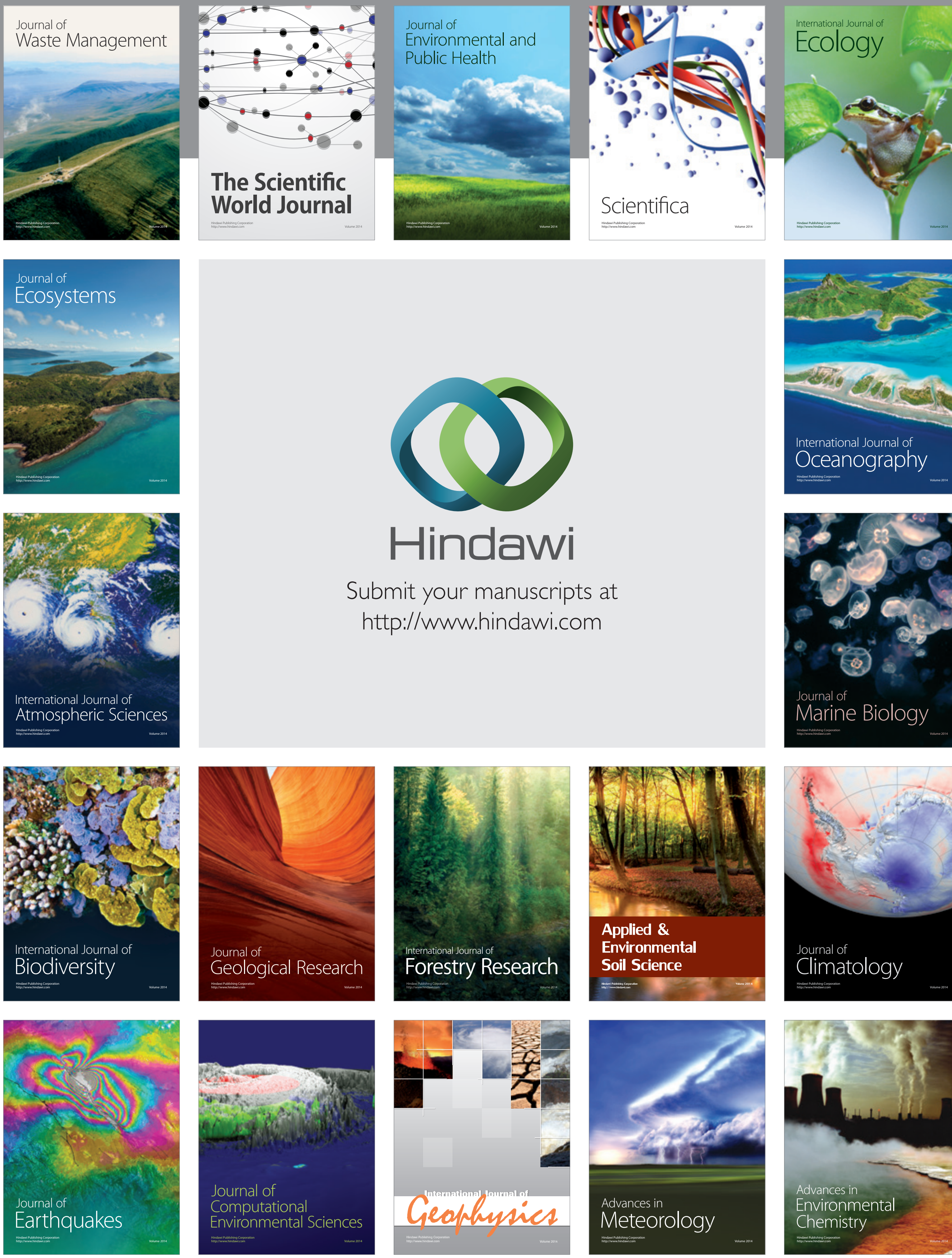
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