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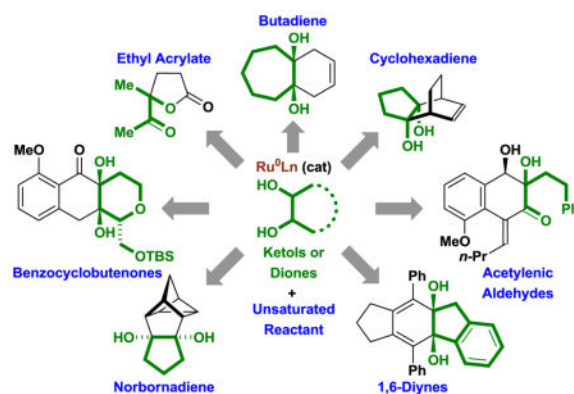
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## Ruthenium(0) Catalyzed Cycloaddition of 1,2-Diols, Ketols or Diones *via* Alcohol-Mediated Hydrogen Transfer

Mr. Hiroki Sato, Dr. Ben W. H. Turnbull, Dr. Keisuke Fukaya, and Prof. Michael J. Krische  
University of Texas at Austin, Department of Chemistry, Welch Hall (A5300), 105 E 24<sup>th</sup> St.,  
Austin, TX 78712, USA

### Put a Ring on It

Merging the characteristics of transfer hydrogenation and carbonyl addition, a broad new class of ruthenium(0) catalyzed cycloadditions has been developed. Fused or bridged bicyclic ring systems are accessible in a redox-independent manner in C-C bond forming hydrogen transfer reactions of diols,  $\alpha$ -ketols or 1,2-diones with diverse unsaturated reactants.



### Keywords

Cycloaddition; Hydrogen Transfer; Ruthenium; Diol; Alcohol; C-C Bond Formation

### 1. Introduction

Since the advent of photocycloaddition (1908)<sup>[1a]</sup> and the Diels-Alder reaction (1928)<sup>[1b]</sup> many distinct and powerful classes of cycloadditions have been developed, including metal catalyzed processes.<sup>[2]</sup> As illustrated by ethylene glycol ( $23 \times 10^6$  tons in 2015) and propylene glycol ( $1.8 \times 10^6$  tons in 2015),<sup>[3c]</sup> diols are high-volume commodity chemicals that are of interest *vis-a-vis* biomass conversion.<sup>[3]</sup> Diols also appear ubiquitously as intermediate or terminal structural elements in target oriented synthesis, which has motivated the development of methods for their formation and elaboration, for example, the interconversion of diols and olefins.<sup>[4,5]</sup> In the course of developing catalytic hydrogen transfer reactions that convert lower alcohols to higher alcohols,<sup>[6]</sup> we recently found that

phosphine-modified zero-valent ruthenium complexes derived from  $\text{Ru}_3(\text{CO})_{12}$  catalyze a diverse array of C-C couplings between vicinally dioxygenated hydrocarbons (diols, ketols, diones) and unsaturated reactants.<sup>[6e]</sup> These transformations occur through a common mechanistic motif in which oxidative formation of ruthenium(II) metalacycles,<sup>[7,8]</sup> which accompanies or triggers dione addition, is followed by diol- or ketol-mediated transfer hydrogenolysis<sup>[9]</sup> of the ruthenacycle to release product, regenerate the dione and return ruthenium to its zero-valent form (Figure 1).

This pattern of reactivity served as the basis for the design of redox-independent cycloadditions between 1,2-diols, ketols or diones with unsaturated partners, including acyclic 1,3-dienes,<sup>[10]</sup> cyclic 1,3-dienes,<sup>[11]</sup> norbornadienes and trienes,<sup>[11]</sup>  $\alpha,\beta$ -unsaturated esters,<sup>[12]</sup> benzannulated diynes<sup>[13a]</sup> and acetylenic aldehydes,<sup>[13b]</sup> 1,6-diynes<sup>[14]</sup> and benzocyclobutenones (Figure 2).<sup>[15]</sup> In this review, we provide an overview of transfer hydrogenative cycloadditions to form fused and bicyclic carbocyclic ring systems via metal catalyzed cycloadditions.<sup>[10–15]</sup> These processes, which occur through formal alcohol C-H functionalization, may be distinguished from related ring forming reactions that involve alcohol substitution *via* dehydrogenation-condensation-reduction (so-called “borrowing hydrogen” processes), which are largely restricted to heterocycle formation.<sup>[16]</sup>

## 2. 1,3-Dienes, Norbornadienes and Trienes

In ruthenium(0) catalyzed hydrohydroxyalkylations of isoprene or myrcene mediated by  $\alpha$ -hydroxy esters,<sup>[17]</sup> mononuclear<sup>[18]</sup> oxaruthenacycles were postulated as reactive intermediates. These metalacycles were isolated, characterized and their reversible formation was demonstrated.<sup>[8]</sup> The allylruthenium moiety embedded in these metalacycles evoked the possibility of tandem C-C bond forming processes wherein oxidative coupling is followed by intramolecular allylation onto a tethered carbonyl partner to form products of cycloaddition. This possibility was initially realized in reactions of acyclic 1,3-dienes with diols.<sup>[10]</sup> Specifically, using the ruthenium(0) catalyst generated from  $\text{Ru}_3(\text{CO})_{12}$  and various chelating phosphine ligands, cycloalkane diols react with the feedstock dienes butadiene, isoprene and myrcene to form fused carbocycles bearing diols at the ring junction (Table 1). The *cis*- or *trans*-diols react with equal facility. Additionally, acyclic diols participate in cycloaddition to form monocyclic adducts.

Diol-diene cycloaddition is an oxidative process in which one equivalent of diene is required as hydrogen acceptor. The cycloaddition of  $\alpha$ -ketols with dienes occurs under identical conditions and is a redox neutral process. Corresponding reductive cycloadditions of diones with dienes employing formic acid as terminal reductant have also been developed. Thus, ruthenium catalyzed [4+2] cycloaddition may be conducted from the diol, ketol or dione oxidation levels (Scheme 1).<sup>[10a]</sup>

Tandem cycloaddition-dehydration provides a novel protocol for benzannulation.<sup>[10c]</sup> For example, the indicated acenaphthalene diol reacts with various butadienes to furnish cycloadducts that aromatize under the conditions of acid catalysis to form substituted fluoranthenes (Scheme 2). Substoichiometric quantities of 3,5-dimethylbenzoic acid

improve conversion by catalyzing alcohol exchange and transfer hydrogenolysis of certain oxaruthenacycle intermediates.<sup>[19]</sup>

The diol-mediated cycloaddition of cyclohexadiene would enable access to bridged carbocycles. However, aromatization of cyclohexadiene to form benzene rendered the feasibility of this process uncertain. In the event, the reaction of cyclohexadiene to cyclic or acyclic diols in the presence of a dppe-modified ruthenium(0) catalyst, good to excellent isolated yields of the [4+2] cycloadducts were obtained with complete *exo*-selectivity as determined by <sup>1</sup>H NMR analysis (Scheme 3).<sup>[11]</sup>

The ability of Ru<sub>3</sub>(CO)<sub>12</sub> to catalyze olefin isomerization<sup>[20]</sup> enables recruitment of non-conjugated dienes in diol-mediated [4+2] cycloaddition with efficiencies roughly equivalent to that observed for the corresponding conjugated dienes (Scheme 4).<sup>[10a,11]</sup> A remarkable application of tandem olefin isomerization-cycloaddition is found in the reaction of 1,5,9-cyclododecatriene. A transient 1,3,5-triene is formed that exists in equilibrium with the corresponding diene-containing [6.4.0] bicycle, which is converted to the indicated bridged polycycle as a single diastereomer.

Mirroring the behavior of conjugated dienes, norbornadiene is known to participate in thermal *homo*-Diels-Alder reactions<sup>[21]</sup> and related metal catalyzed cycloadditions.<sup>[22]</sup> Based on this precedent, the diol-mediated cycloaddition of norbornadiene was explored.<sup>[11]</sup> Using the ruthenium(0) catalyst modified by dppe, cycloadducts were formed in good isolated yields with complete levels of *exo*-selectivity as determined by <sup>1</sup>H NMR (Scheme 5).

As demonstrated in the cycloaddition of diols with acyclic dienes, cyclohexadiene and norbornadiene also are capable of engaging in redox-independent cycloaddition (Scheme 6).<sup>[11]</sup> That is, cycloadditions may be conducted in oxidative, redox-neutral and reductive cycloaddition modes. In the latter case, formic acid is employed as terminal reductant.

### 3. Acrylates and Unsaturated Esters

Spiro- and  $\alpha$ -methylene- $\gamma$ -butyrolactones are frequently encountered as structural motifs in natural products<sup>[23]</sup> and fragrance compounds.<sup>[24]</sup> It was posited that oxaruthenacycles obtained through ruthenium(0) mediated oxidative coupling of vicinal diones with  $\alpha,\beta$ -unsaturated esters could undergo cyclization to form  $\gamma$ -lactones.<sup>[12]</sup> In the event, using the ruthenium(0) catalyst derived from Ru<sub>3</sub>(CO)<sub>12</sub> and dppp, a variety of cyclic and acyclic diols react with methyl acrylate to form  $\gamma$ -lactones in good to excellent yields (Table 2).

Attempted ruthenium(0) catalyzed cycloadditions of  $\beta$ -substituted acrylic esters with cyclic and acyclic diols did not provide the desired lactone products. However, it was found that *N*-benzyl-3-hydroxy-2-oxindole reacts readily with  $\beta$ -substituted  $\alpha,\beta$ -unsaturated esters due to the exceptional reactivity of the vicinal dicarbonyl moiety of the transient isatin. In these redox-neutral processes, spiro-lactones are formed in good to excellent isolated yields with complete control of diastereoselectivity as determined by <sup>1</sup>H NMR analysis (Scheme 7).<sup>[12]</sup>

The lack of reactivity observed in attempted reactions of substituted acrylic esters with cyclic and acyclic diols may be attributed to unfavorable equilibria evident in reversible oxaruthenacycle formation.<sup>[8]</sup> For oxaruthenacycles bearing suitably disposed leaving groups, elimination might drive formation of the C-C coupling product. The veracity of this hypothesis is demonstrated in cycloadditions of cyclic and acyclic diols with the indicated  $\alpha$ -hydroxymethyl-substituted acrylic ester, where elimination of water enables formation of  $\alpha$ -*exo*-methylene  $\gamma$ -butyrolactones (Scheme 8).<sup>[12]</sup>

As illustrated in the cycloaddition of hydrobenzoin, benzoin and benzil with methyl acrylate, lactone formation may be accomplished in oxidative, redox-neutral or reductive modes from the diol, ketol or dione oxidation levels, respectively. The latter reaction of benzil employs 2-propanol (300 mol%) as terminal reductant (Scheme 9).<sup>[12]</sup>

#### 4. Benzannulated Diynes and *ortho*-Acetylenic Benzaldehydes

The ruthenium(0) catalyzed reaction of 3,4-benzannulated 1,5-diynes with  $\alpha$ -ketols occurs through successive alkyne-carbonyl oxidative coupling events to form products of [4+2] cycloaddition.<sup>[13a]</sup> To suppress alkyne reduction, the reaction is conducted in a redox-neutral manner from the hydroxyketone oxidation level rather than using diol reactants, which requires a sacrificial hydrogen acceptor. The cycloadditions proceed at relatively low temperatures in aqueous organic media. As anticipated based on corresponding reactions of mono-alkynes,<sup>[19b]</sup> each alkyne-carbonyl oxidative coupling event occurs in a regioselective fashion at the aryl-substituted alkyne terminus (Scheme 10).

The regioselective cycloaddition of non-symmetric diynes is achieved through differential substitution of the alkyne termini by *n*-propyl and *t*-butyl groups (Scheme 11). Ruthenium(0)-mediated alkyne-carbonyl oxidative coupling occurs initially at the less sterically demanding *n*-propyl substituted alkyne. After a second oxidative coupling at the *t*-butyl substituted alkyne and transfer hydrogenolysis of the resulting oxaruthenacycle, the cycloadduct is obtained as a single constitutional isomer.

Through the use of ruthenium(0) complexes modified by CyJohnPhos or RuPhos, *ortho*-acetylenic benzaldehydes react with  $\alpha$ -ketols to form products of [4+2] cycloaddition (Table 3).<sup>[13b]</sup> As in related reactions of 3,4-benzannulated 1,5-diynes,<sup>[13a]</sup> a catalytic mechanism involving successive oxidative coupling events is proposed. However, in the case of *ortho*-acetylenic benzaldehydes, alkyne-carbonyl oxidative coupling is followed by aldehyde-dione oxidative coupling. Notably, all C-C coupling events occurs in a highly regio- and stereoselective fashion to deliver cycloadducts as single diastereomers.

#### 5. 1,6-Diynes

Metal catalyzed [2+2+2] cycloadditions enable convergent construction of (poly)cyclic molecules from  $\pi$ -unsaturated reactants.<sup>[2c,2e,25]</sup> In the presence of ruthenium(0) catalysts, 1,6-diynes form ruthenacyclopentadienes that participate in successive carbonyl addition with transient diones derived from diol reactants to form products of [2+2+2] cycloaddition (Table 4).<sup>[14]</sup> Structurally diverse cyclic and acyclic diols deliver cycloadducts with complete levels of *syn*-diastereoselectivity as determined by <sup>1</sup>H NMR analysis. A carboxylic

acid cocatalyst was again required to enhance rate and conversion.<sup>[19]</sup> 1,6-Diynes that are unsubstituted at the acetylenic terminus and 1,7-diynes are not efficient partners for cycloaddition under these initially developed conditions.

As cycloaddition occurs through a catalytic mechanism involving successive dehydrogenation of the diol reactant to form a transient  $\alpha$ -ketol and, ultimately, the vicinal dione required for C-C bond formation, diols,  $\alpha$ -ketols and vicinal diones should all be competent partners for [2+2+2] cycloaddition. Indeed, beyond oxidative [2+2+2] cycloadditions of diol reactants, redox-neutral cycloadditions of  $\alpha$ -ketols and reductive cycloadditions of diones are possible (Scheme 12). In the latter case, 2-propanol serves as terminal reductant.

## 6. Benzocyclobutenones

The preceding transformations suggested the feasibility of exploiting ruthenacycles derived upon C-C bond oxidative addition<sup>[26]</sup> as partners for cycloaddition. Given reports on the intermolecular cycloadditions of (benzo)cyclobutenone derivatives catalyzed by nickel,<sup>[27]</sup> palladium,<sup>[28]</sup> rhodium<sup>[29]</sup> and ruthenium,<sup>[30]</sup> the formal insertion of adjacent diol carbon atoms into C-C bonds appeared feasible. In the event, upon exposure to the ruthenium(0) catalyst derived from  $\text{Ru}_3(\text{CO})_{12}$  and dppp, benzocyclobutenones react with 1,2-diols to form cycloadducts with complete levels of diastereoselectivity as determined by  $^1\text{H}$  NMR analysis (Table 5).<sup>[15]</sup> Nonsymmetric diols delivered cycloadducts as single regioisomers. Whereas catalytic processes involving C-C bond activation rely on the insertion of  $\pi$ -unsaturated coupling partners, to our knowledge, the present cycloadditions involve formal insertion of saturated C-H bonds into C-C  $\sigma$ -bonds.

Cycloaddition is possible in oxidative, redox-neutral, and reductive modes (Scheme 13). As corroborated by the isolation of the ring-opened hydrogenolysis product (2-methoxy-6-methylphenyl)methanol, diol cycloadditions are oxidative processes in which excess benzocyclobutenone (50 mol%) accepts two equivalents of hydrogen. Reactions conducted from the ketol oxidation level exploit equimolar quantities of reactant, establishing the practicality of this method for the convergent union of complex fragments. Finally, for reductive cycloaddition from the dione oxidation level, 2-propanol is employed as terminal reductant.

## 7. Conclusion and Outlook

New reactivity is the most fundamental and far-reaching basis for innovation in the field of chemical synthesis. By harnessing the native reducing ability of alcohols, we have developed a broad, new class of metal catalyzed carbonyl additions.<sup>[6]</sup> Beyond bypassing the use of discrete organometallic reagents in known carbonyl additions,<sup>[6g]</sup> the unique mechanisms embodied by these processes have availed transformations that have no counterpart in the current lexicon of synthetic methods. Indeed, the transfer hydrogenative cycloadditions described herein represent an outgrowth of this reactivity pattern that extends beyond the capabilities of classical carbonyl addition and cycloaddition chemistry. It is the authors hope that the present review will accelerate further expansion of this distinctive subset of metal

catalyzed cycloadditions and, more broadly, the development of new alcohol-mediated C-C bond formations.

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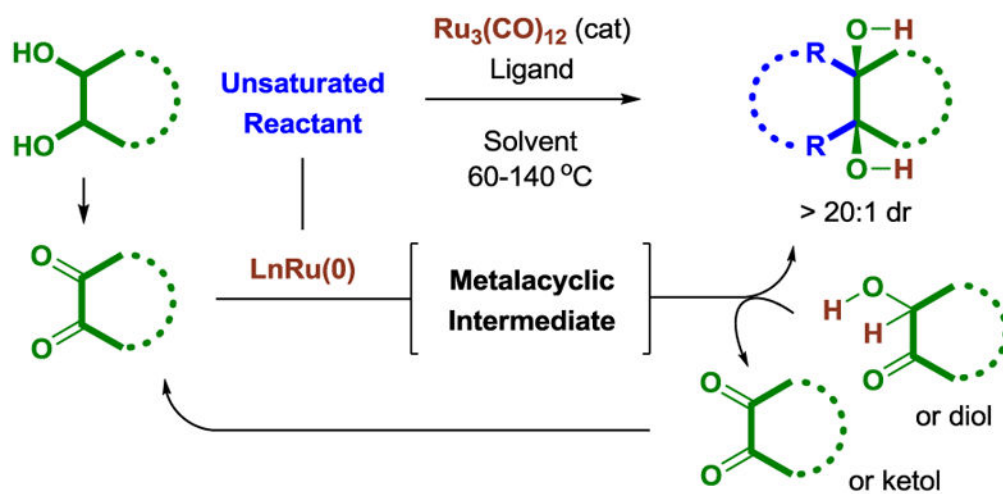
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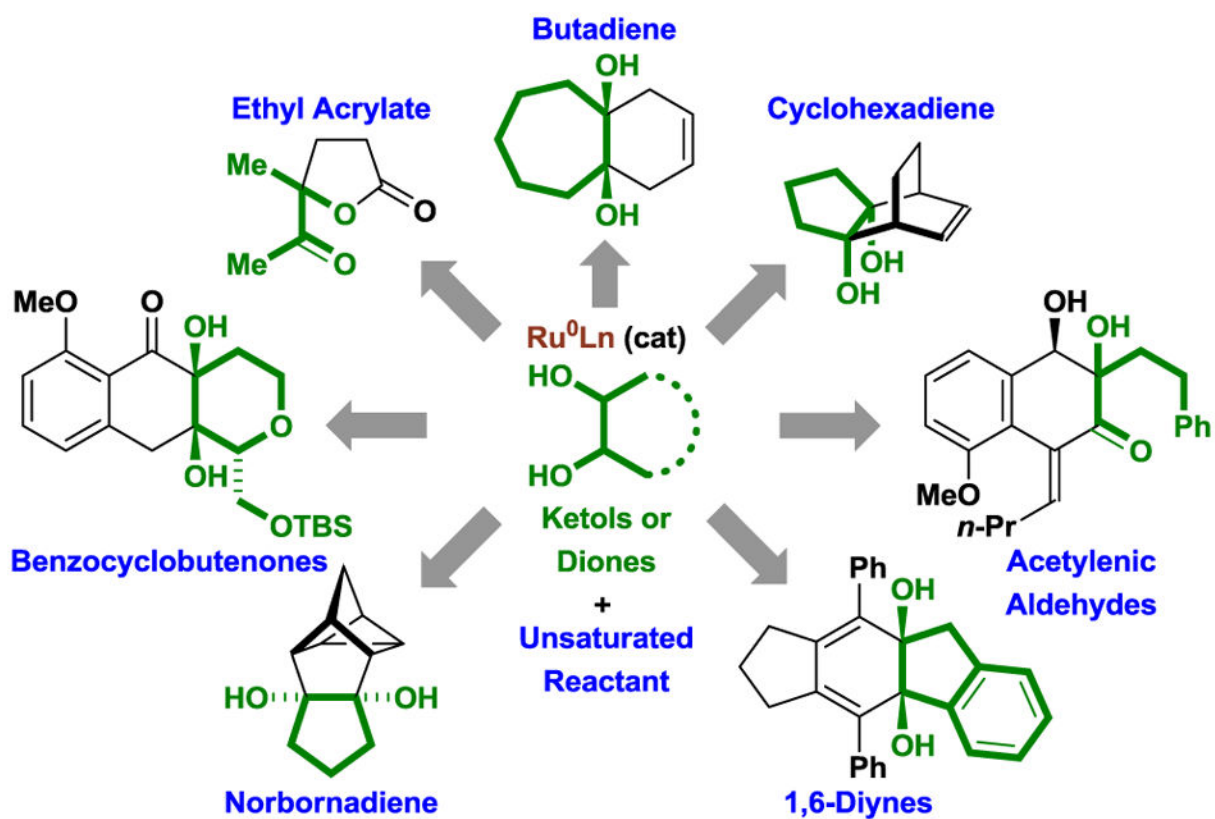
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27. For selected examples of intermolecular nickel catalyzed cycloadditions of cyclobutenone derivatives, see: Huffman MA, Liebeskind LS. *J Am Chem Soc*. 1991; 113:2771–2772. Murakami M, Ashida S, Matsuda T. *J Am Chem Soc*. 2005; 127:6932–6933. [PubMed: 15884919] Auvinet AL, Harrity JPA. *Angew Chem*. 2011; 123:2821–2824. *Angew Chem Int Ed*. 2011; 50:2769–2772. Ho KYT, Aissa C. *Chem Eur J*. 2012; 18:3486–3489. [PubMed: 22359347] Ishida N, Yuhki T, Murakami M. *Org Lett*. 2012; 14:3898–3901. [PubMed: 22799436] Kumar P, Louie J. *Org Lett*. 2012; 14:2026–2029. [PubMed: 22468962] Thakur A, Evangelista JL, Kumar P, Louie J. *J Org Chem*. 2015; 80:9951–9958. [PubMed: 26412483] Stalling T, Harker WRR, Auvinet AL, Cornet EJ, Harrity JPA. *Chem Eur J*. 2015; 21:2701–2704. [PubMed: 25491134]
28. For an example of the intermolecular palladium catalyzed cycloaddition of cyclobutanone derivatives, see: Okumura S, Sun F, Ishida N, Murakami M. *J Am Chem Soc*. 2017; 139:12414–12417. [PubMed: 28837766]
29. For selected examples of intermolecular rhodium catalyzed cycloadditions of cyclobutenone derivatives, see: Kondo T, Taguchi Y, Kaneko Y, Niimi M, Mitsudo T. *Angew Chem*. 2004; 116:5483–5486. *Angew Chem Int Ed*. 2004; 43:5369–5372. Kondo T, Niimi M, Nomura M, Wada K, Mitsudo T-a. *Tetrahedron Lett*. 2007; 48:2837–2839.
30. For an example of the intermolecular ruthenium catalyzed cycloaddition of cyclobutenone derivatives, see: Kondo T, Nakamura A, Okada T, Suzuki N, Wada K, Mitsudo T. *J Am Chem Soc*. 2000; 122:6319–6320.

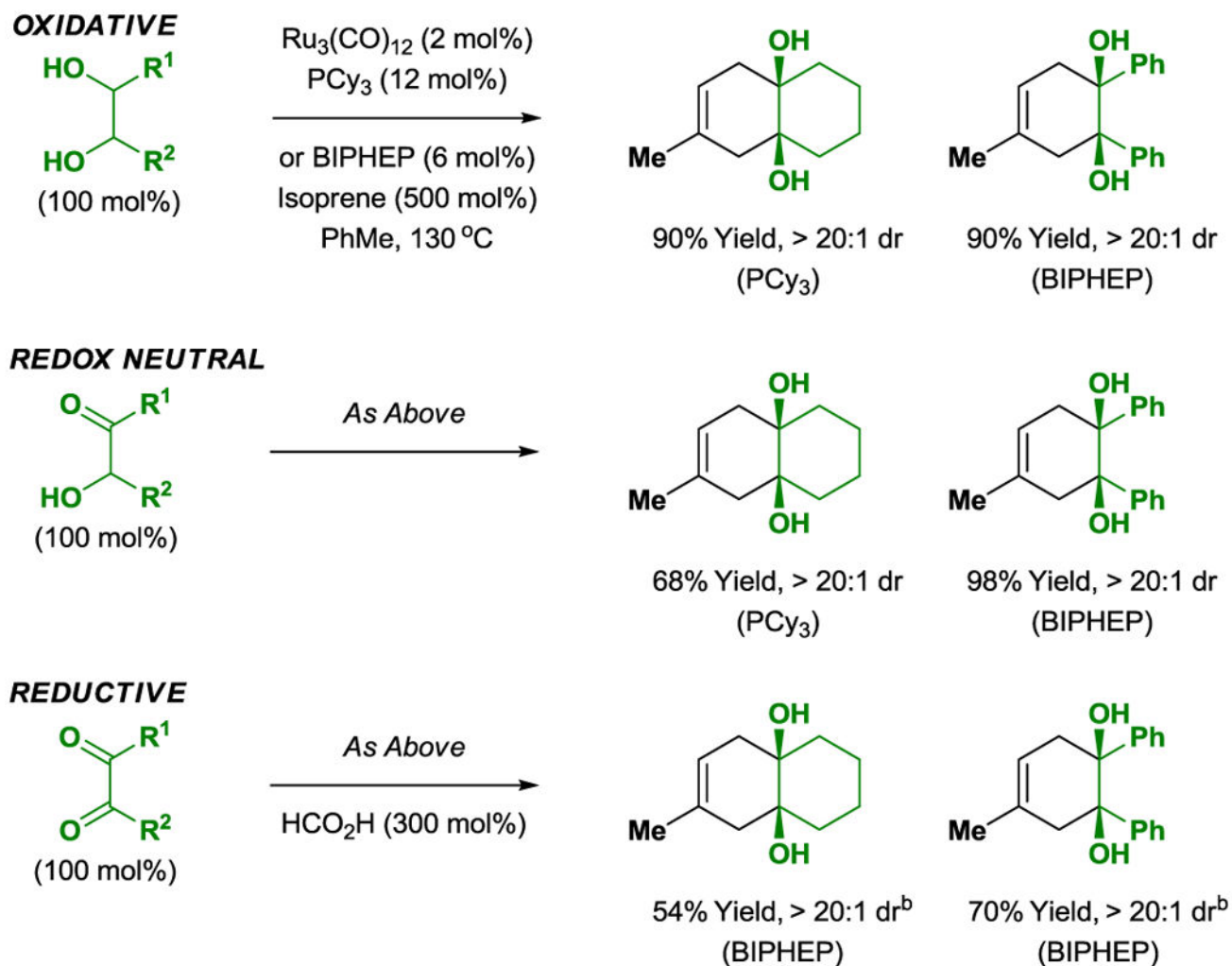




**Figure 1.**  
General catalytic mechanism for ruthenium(0) catalyzed cycloaddition of 1,2-diols

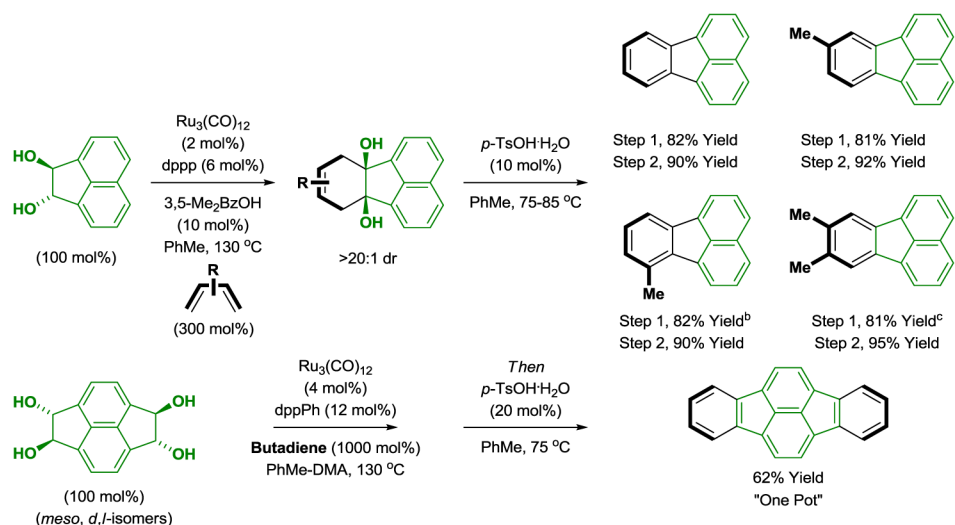


**Figure 2.** Ruthenium(0) catalyzed cycloaddition of diols, ketols or diones via alcohol-mediated hydrogen transfer.

**Scheme 1.**

Redox independent [4+2] cycloaddition of diols, ketols and diones with isoprene.<sup>a</sup>

<sup>a</sup>Yields are of material isolated by silica gel chromatography. BIPHEP = 2,2'-bis-(diphenylphosphino)-1,1'-biphenyl. <sup>b</sup> $\text{RuH}_2\text{CO}(\text{PPh}_3)_3$  (6 mol%).

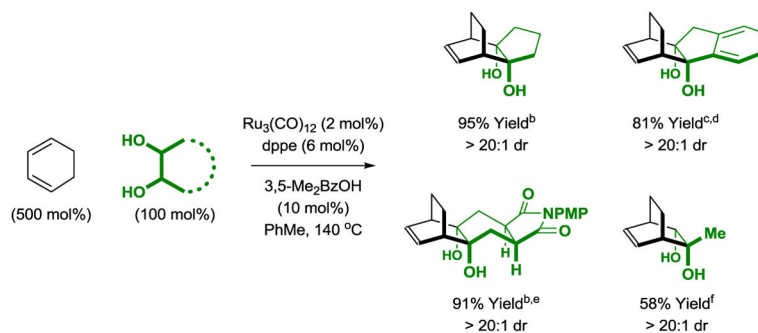
**Scheme 2.**

Ruthenium(0) catalyzed diol-diene benzannulation to form substituted fluoranthenes.<sup>a</sup>

<sup>a</sup>Yields are of material isolated by silica gel chromatography. dppp = *bis*-

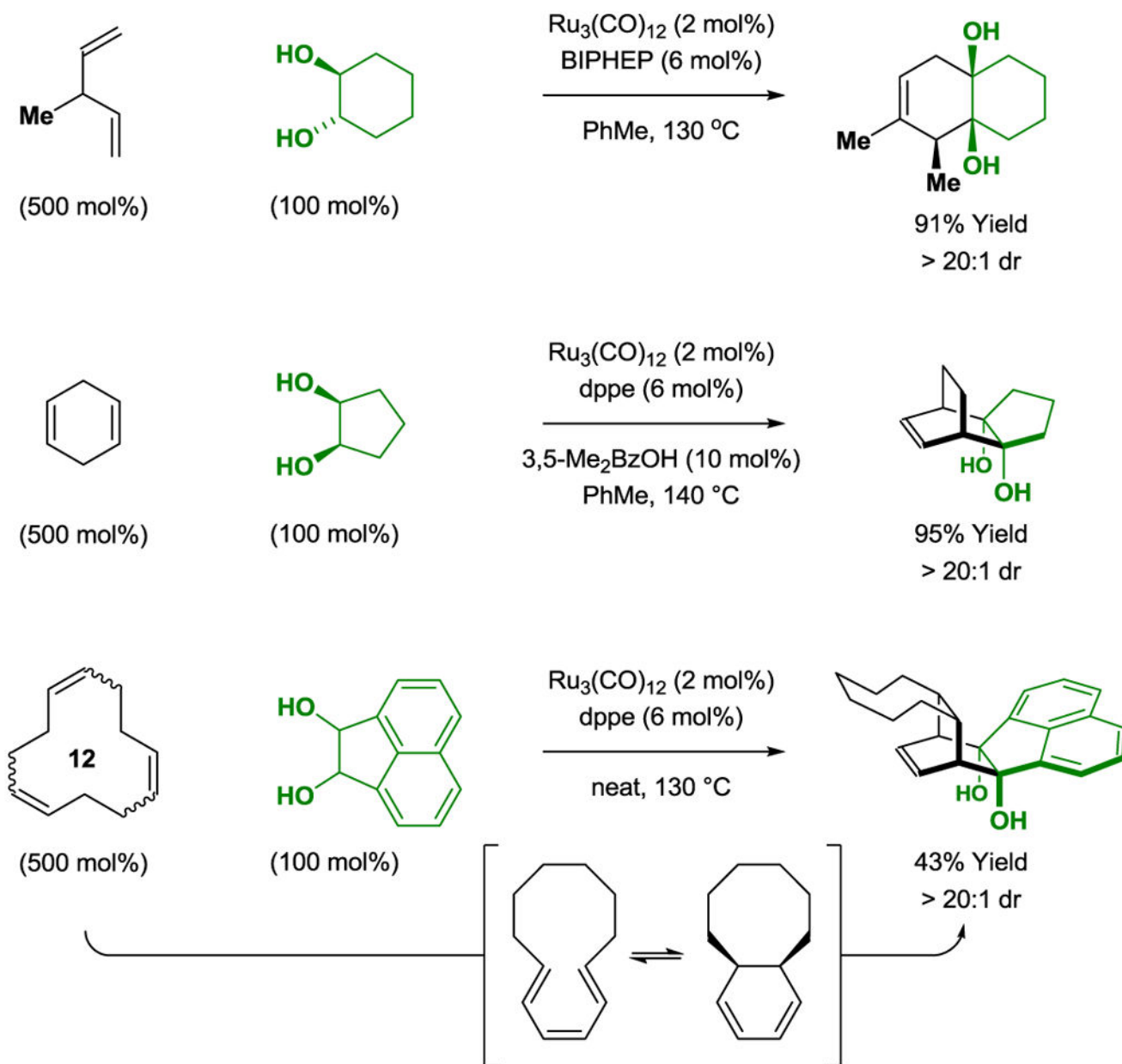
(diphenylphosphino)propane. dppPh = *bis*-(1,2-diphenylphosphino)benzene. <sup>b</sup>120 °C.

<sup>c</sup>dppPh, 3,5-Me<sub>2</sub>BzOH was omitted.

**Scheme 3.**

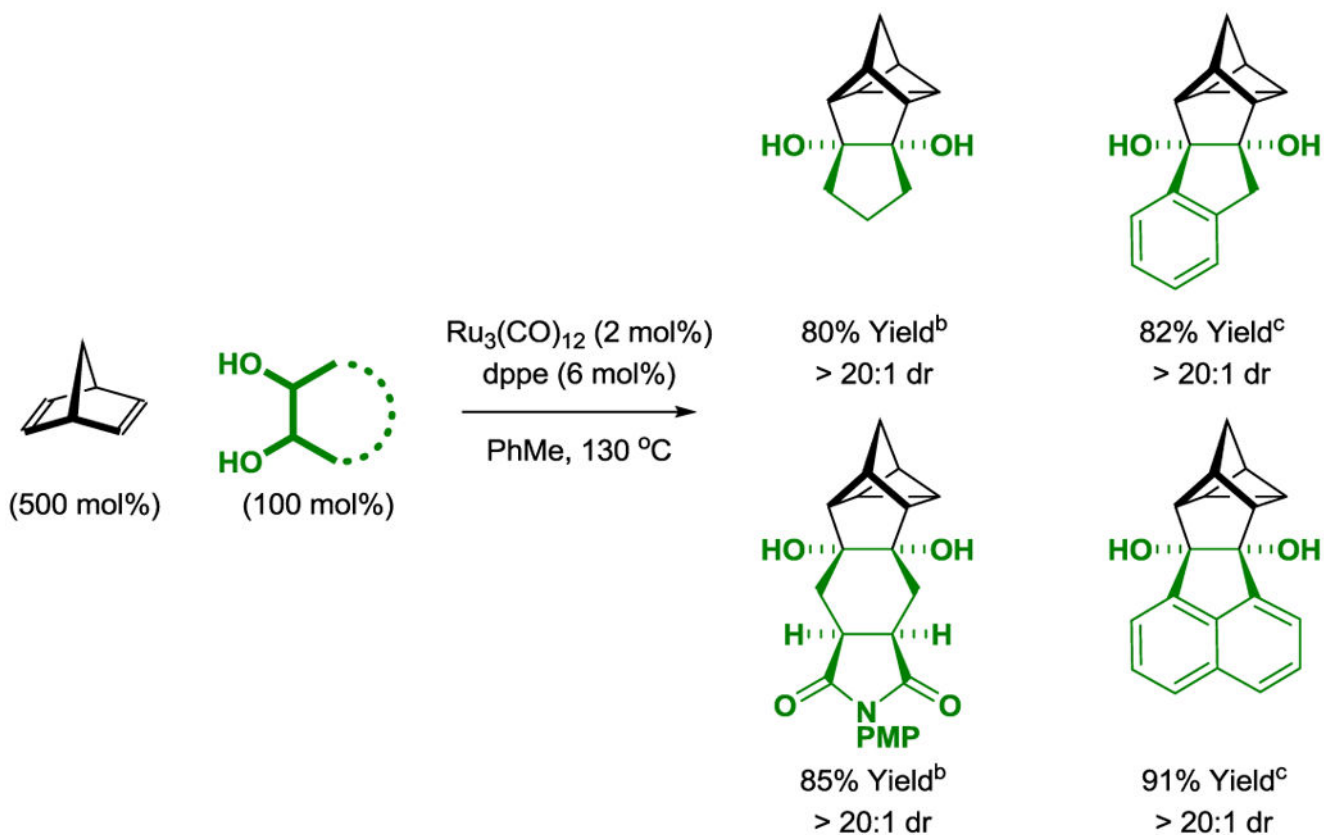
*exo*-Selective ruthenium(0) catalyzed [4+2] cycloaddition of cyclohexadiene.<sup>a</sup>

<sup>a</sup>Yields are of material isolated by silica gel chromatography. dppe = *bis*-(diphenylphosphino)ethane. <sup>b</sup>The *cis*-1,2-diol was employed. <sup>c</sup>A mixture of *cis*- and *trans*-1,2-diols was employed. <sup>d</sup>*rac*-BINAP (6 mol%), BINAP = 2,2'-*bis*-(diphenylphosphino)-1,1'-binaphthalene. <sup>e</sup>3,5-Me<sub>2</sub>BzOH was omitted, 150 °C. <sup>f</sup>dCype (6 mol%), dCype = *bis*-(dicyclohexylphosphino)ethane. A 13% yield of the ketol cycloadduct also was obtained.

**Scheme 4.**

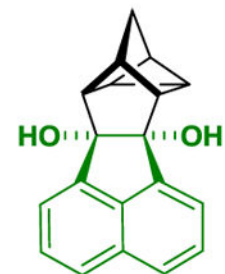
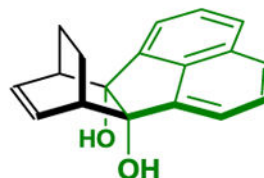
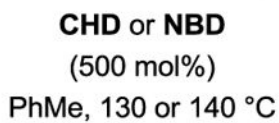
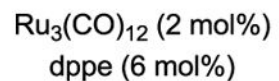
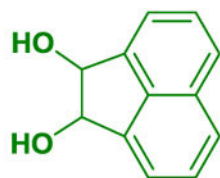
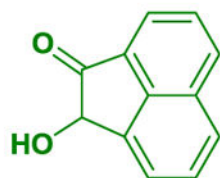
Tandem ruthenium(0) catalyzed olefin isomerization [4+2] cycloaddition of diols with non-conjugated dienes and 1,5,9-cyclododecatriene.<sup>a</sup>

<sup>a</sup>Yields are of material isolated by silica gel chromatography. BIPHEP = 2,2'-bis-(diphenylphosphino)-1,1'-biphenyl. dppe = bis-(diphenylphosphino)ethane.

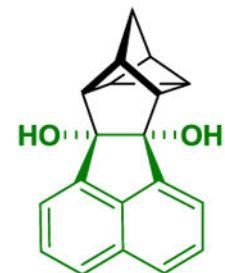
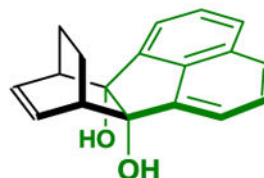
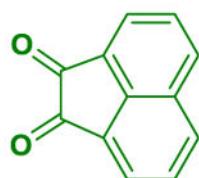
**Scheme 5.**

*exo*-Selective ruthenium(0) catalyzed cycloaddition of norbornadiene.<sup>a</sup>

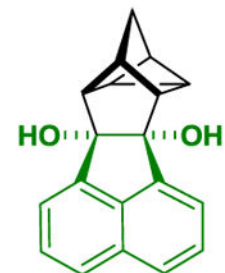
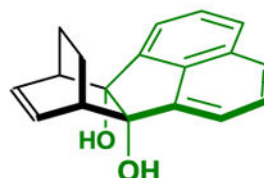
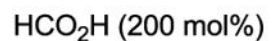
<sup>a</sup>Yields are of material isolated by silica gel chromatography. dppe = *bis*-(diphenylphosphino)ethane. <sup>b</sup>The *cis*-1,2-diol was employed. <sup>c</sup>A mixture of *cis*- and *trans*-1,2-diols was employed.

**OXIDATIVE****REDOX NEUTRAL**

As Above

**REDUCTIVE**

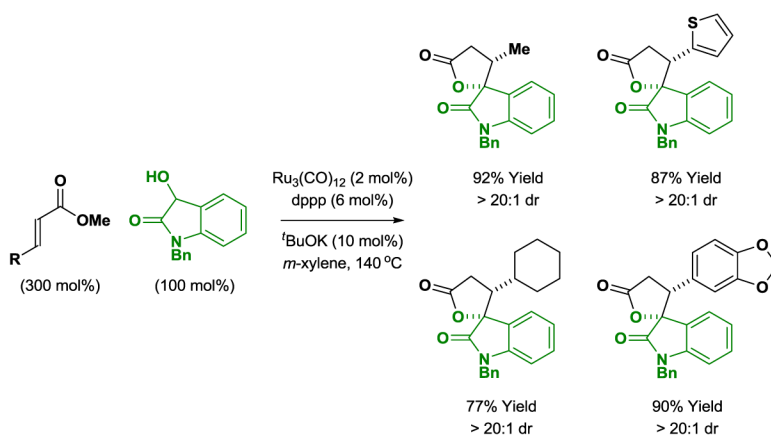
As Above

**Scheme 6.**

Redox independent cycloaddition of diols, ketols and diones with cyclohexadiene or norbornadiene.<sup>a</sup>

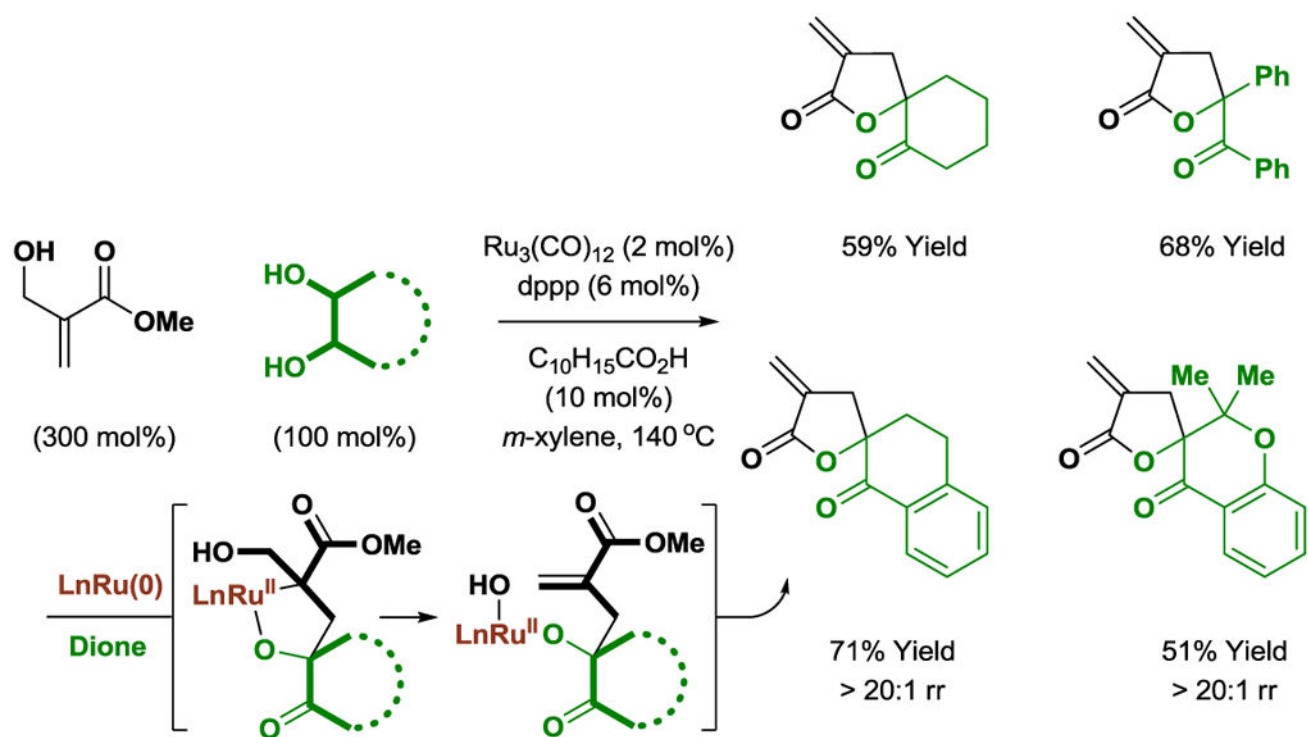
<sup>a</sup>Yields are of material isolated by silica gel chromatography. dppe = *bis*-(diphenylphosphino)ethane. <sup>b</sup>3,5-Me<sub>2</sub>BzOH (10 mol%).



**Scheme 7.**

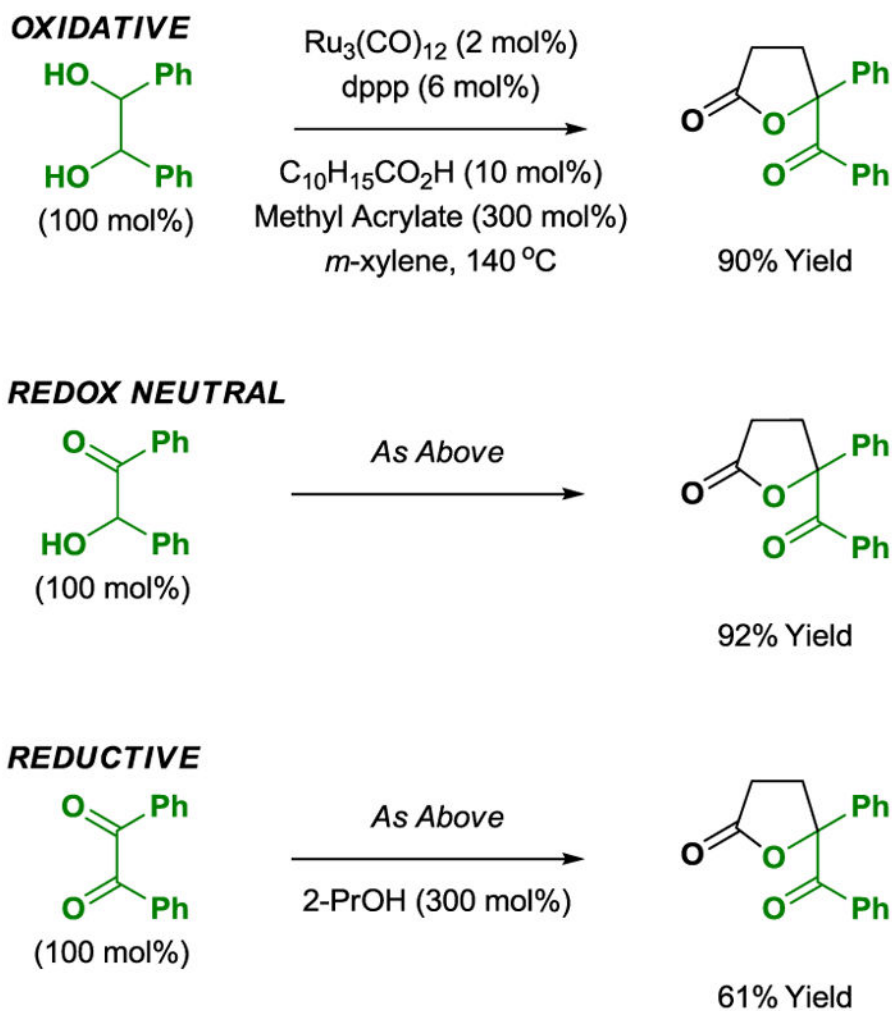
Ruthenium(0) catalyzed [3+2] cycloaddition of *N*-benzyl-3-hydroxy-2-oxindole with substituted  $\alpha,\beta$ -unsaturated esters to form spiro lactones.<sup>a</sup>

<sup>a</sup>Yields are of material isolated by silica gel chromatography. dppp = *bis*-(diphenylphosphino)propane.

**Scheme 8.**

Ruthenium(0) catalyzed [3+2] cycloaddition with an  $\alpha$ -hydroxymethyl-substituted  $\alpha,\beta$ -unsaturated ester to form  $\alpha$ -*exo*-methylene- $\gamma$ -butyrolactones.<sup>a</sup>

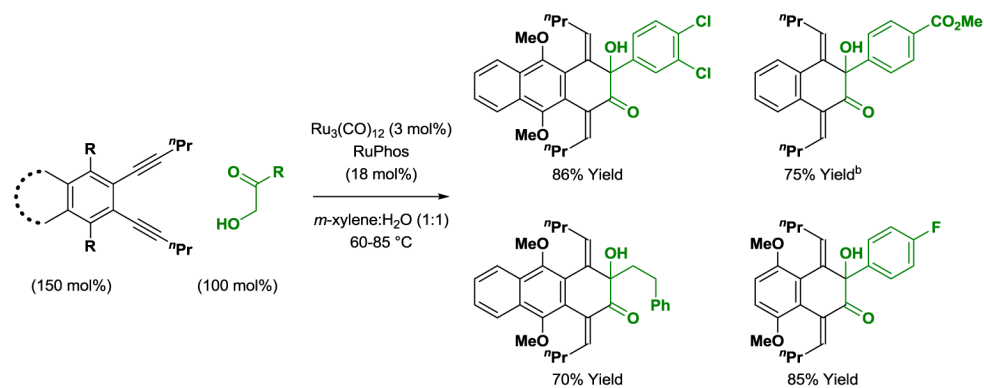
<sup>a</sup>Yields are of material isolated by silica gel chromatography. dppp = *bis*-(diphenylphosphino)propane.  $\text{C}_{10}\text{H}_{15}\text{CO}_2\text{H}$  refers to 1-adamantanecarboxylic acid.

**Scheme 9.**

Redox independent [3+2] cycloaddition of hydrobenzoin, benzoin and benzil with methyl acrylate.<sup>a</sup>

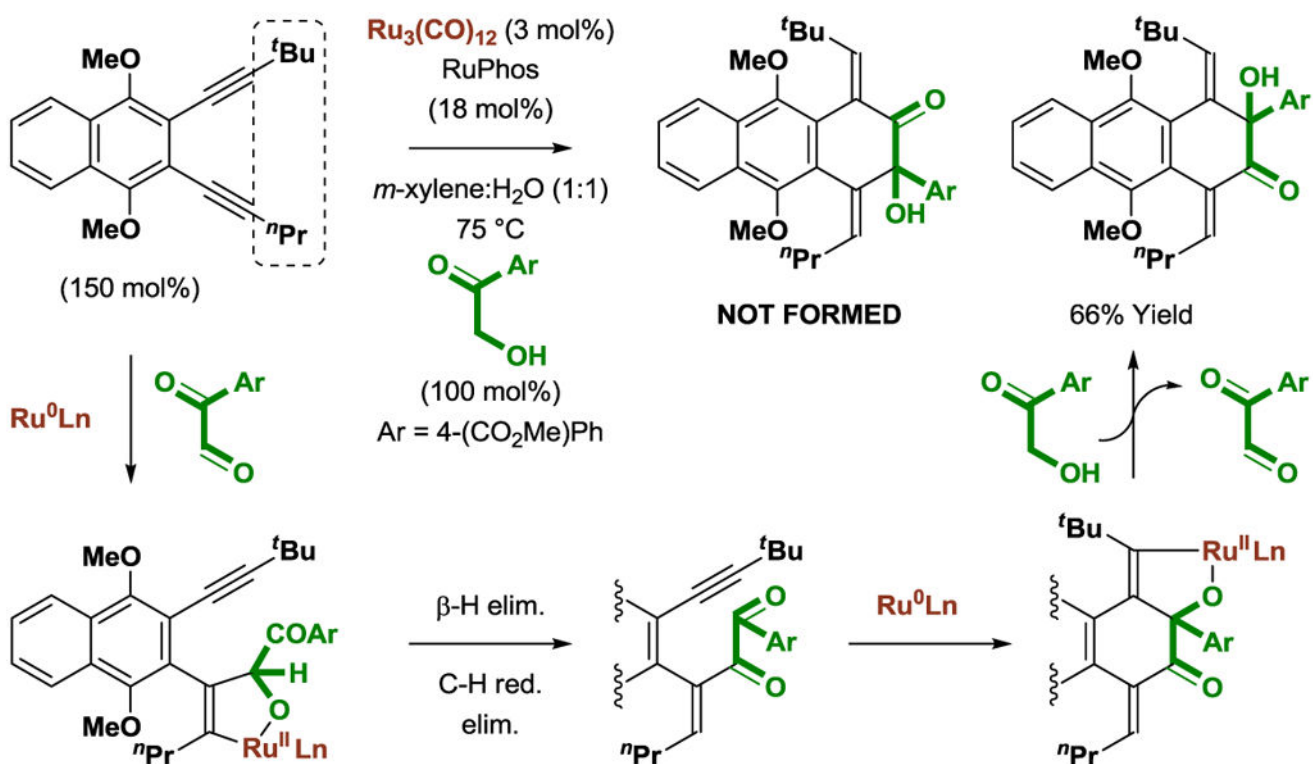
<sup>a</sup>Yields are of material isolated by silica gel chromatography. dppp = *bis*-

(diphenylphosphino)propane.  $\text{C}_{10}\text{H}_{15}\text{CO}_2\text{H}$  refers to 1-adamantanecarboxylic acid.

**Scheme 10.**

Ruthenium(0) catalyzed [4+2] cycloaddition of 3,4-benzannulated 1,5-diyne with  $\alpha$ -ketols.<sup>a</sup>

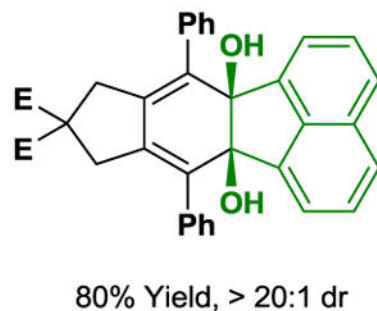
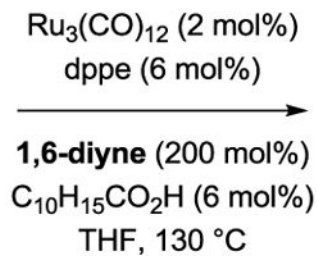
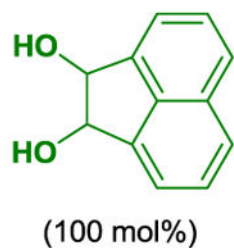
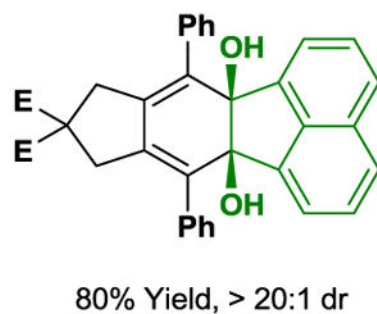
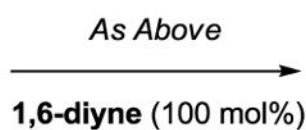
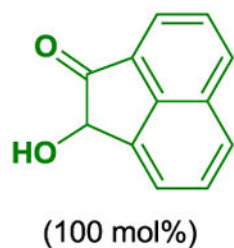
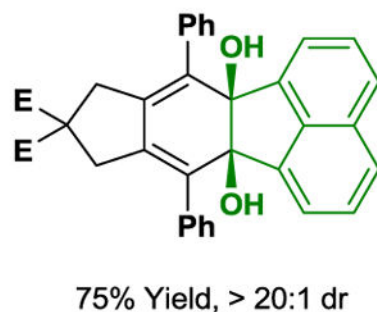
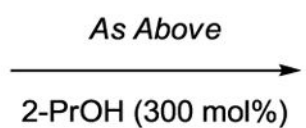
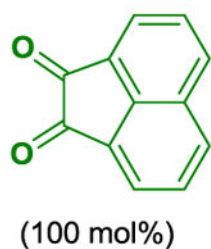
<sup>a</sup>Yields are of material isolated by silica gel chromatography. RuPhos = 2-dicyclohexylphosphino-2',6'-diisopropoxybiphenyl. <sup>b</sup> $\text{Ru}_3(\text{CO})_{12}$  (2 mol%), CyJohnPhos (12 mol%), CyJohnPhos = 2-(dicyclohexylphosphino)biphenyl.



Scheme 11.

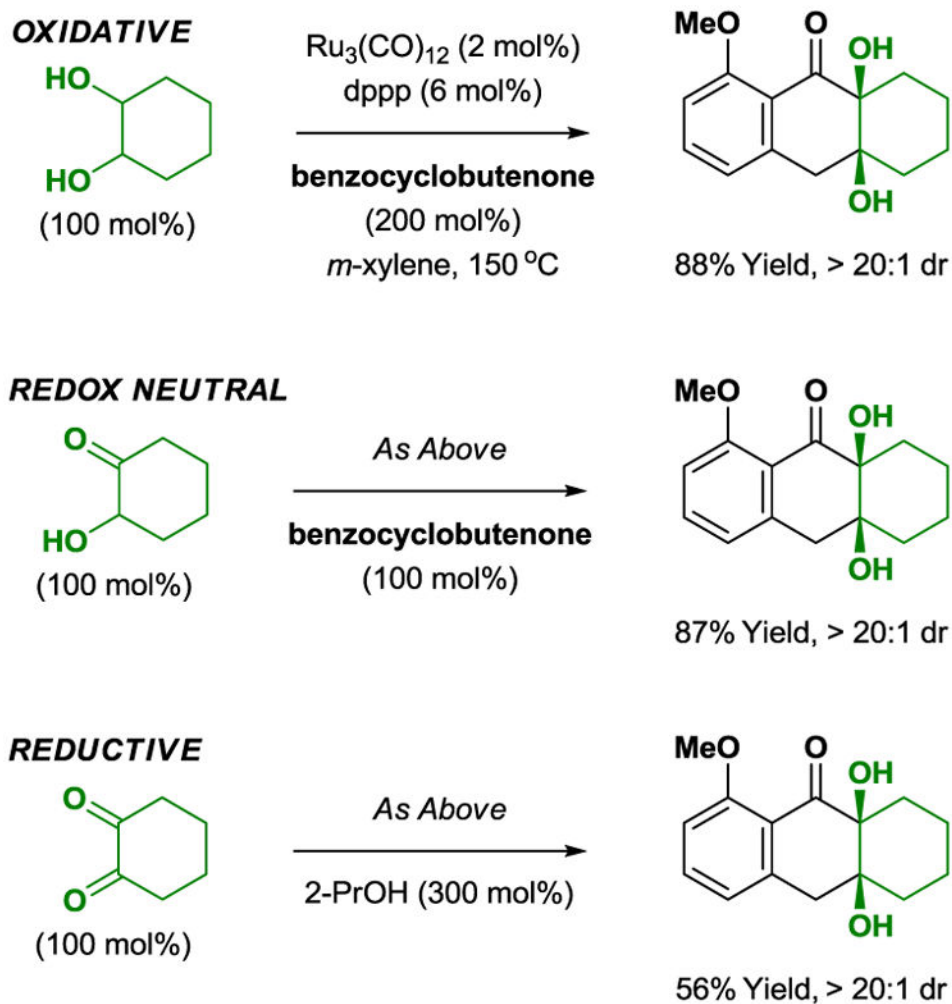
Regioselective ruthenium(0) catalyzed [4+2] cycloaddition of 3,4-benzannulated 1,5-diyne with  $\alpha$ -ketols and general catalytic mechanism.<sup>a</sup>

<sup>a</sup>Yields are of material isolated by silica gel chromatography. RuPhos = 2-dicyclohexylphosphino-2',6'-diisopropoxybiphenyl.

**OXIDATIVE****REDOX NEUTRAL****REDUCTIVE****Scheme 12.**

Redox independent [2+2+2] cycloadditions of diols, ketols and diones with 1,6-diyne.<sup>a</sup>

<sup>a</sup>Yields are of material isolated by silica gel chromatography. dppe = *bis*-(diphenylphosphino)ethane.  $\text{C}_{10}\text{H}_{15}\text{CO}_2\text{H}$  refers to 1-adamantanecarboxylic acid.

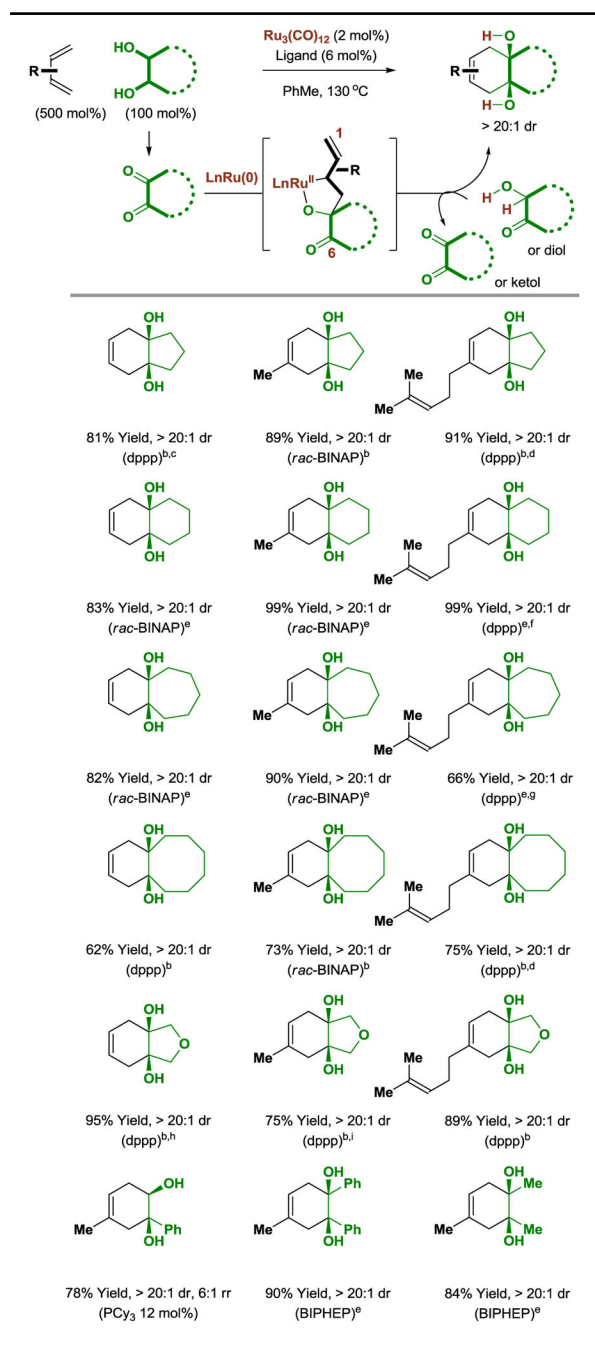
**Scheme 13.**

Redox independent [4+2] cycloaddition of cyclohexane diols, cyclohexane ketol and cyclohexane dione with a benzocyclobutenone.<sup>a</sup>

<sup>a</sup>Yields are of material isolated by silica gel chromatography. dppp = *bis*-(diphenylphosphino)propane.

Table 1

Ruthenium(0) catalyzed [4+2] cycloaddition of diols with the feedstock dienes butadiene, isoprene and myrcene to form cyclohexene diols.<sup>a</sup>



<sup>a</sup>Yields are of material isolated by silica gel chromatography. dppp = *bis*-(diphenylphosphino)propane. BINAP = 2,2'-*bis*-(diphenylphosphino)-1,1'-binaphthalene. BIPHEP = 2,2'-*bis*-(diphenylphosphino)-1,1'-biphenyl.

<sup>b</sup>The *cis*-1,2-diol was employed.



<sup>c</sup>3,5-Me<sub>2</sub>BzOH (10 mol%), 7 hrs.

<sup>d</sup>3,5-Me<sub>2</sub>BzOH (10 mol%), myrcene (400 mol%).

<sup>e</sup>The *trans*-1,2-diol was employed.

<sup>f</sup>myrcene (300 mol%).

<sup>g</sup>3,5-Me<sub>2</sub>BzOH (10 mol%), 18 hrs, myrcene (400 mol%).

<sup>h</sup>4 hrs, 5:1 mixture of olefin regioisomers.

<sup>i</sup>8 hrs, 14:1 mixture of olefin regioisomers.

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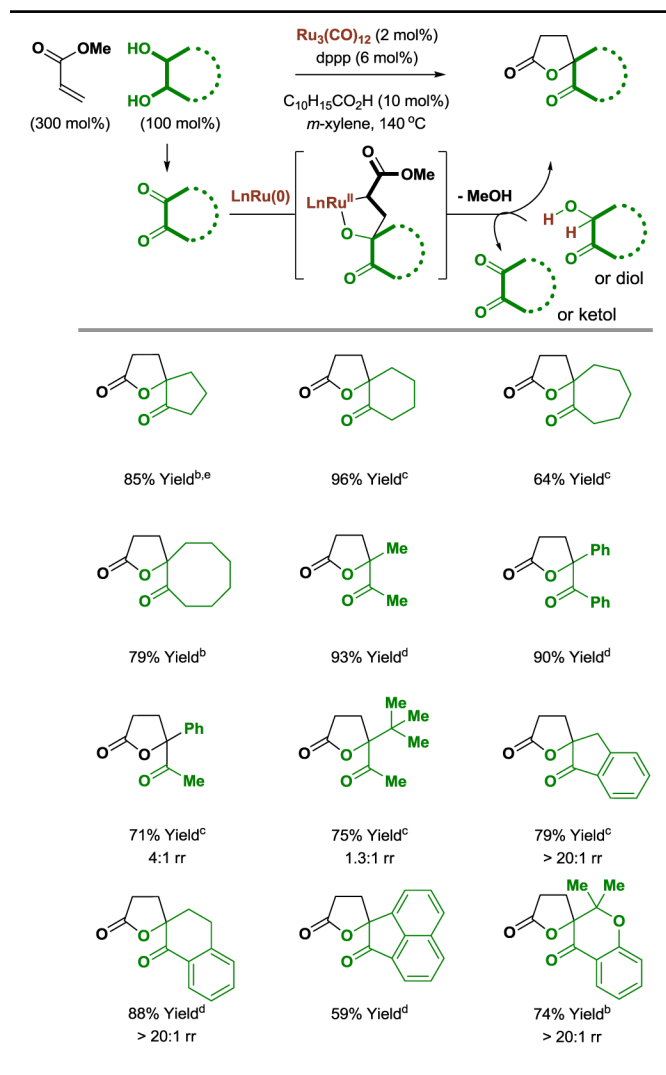
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Table 2

Ruthenium(0) catalyzed [3+2] cycloaddition of methyl acrylate with cyclic and acyclic diols to form  $\gamma$ -lactones.<sup>a</sup>



<sup>a</sup>Yields are of material isolated by silica gel chromatography. dppp = *bis*-(diphenylphosphino)propane.  $\text{C}_{10}\text{H}_{15}\text{CO}_2\text{H}$  refers to 1-adamantanecarboxylic acid.

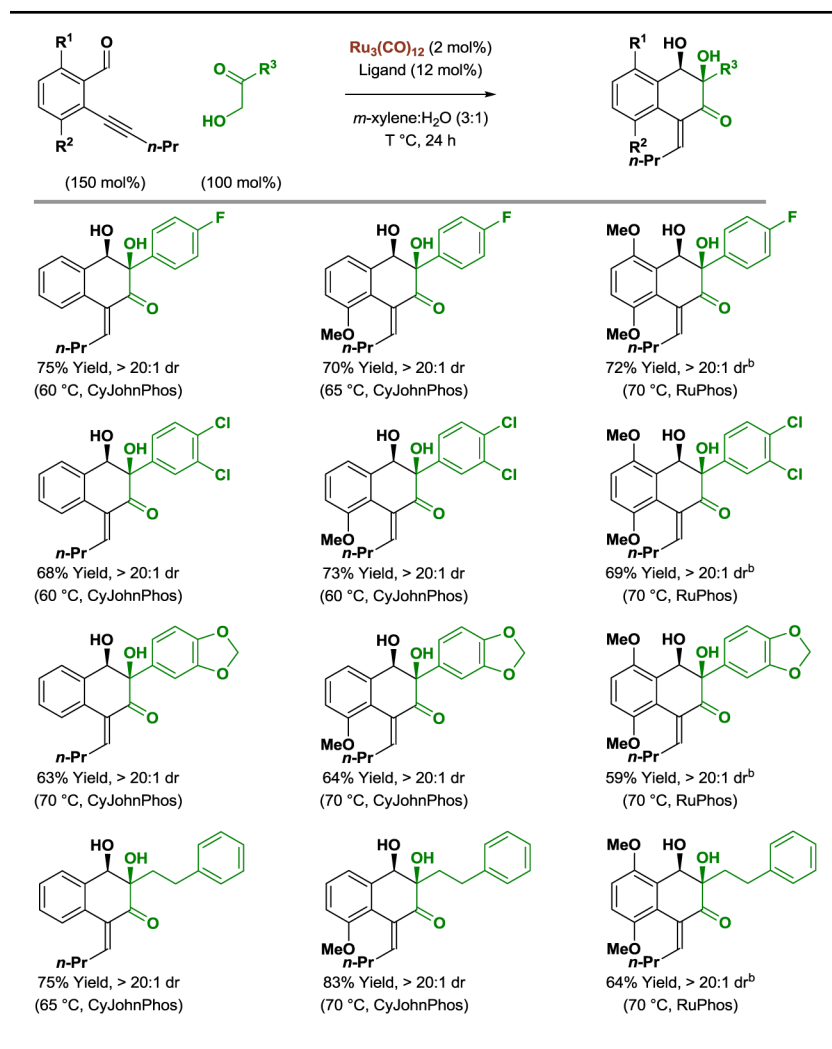
<sup>b</sup>The *cis*-1,2-diol was employed.

<sup>c</sup>The *trans*-1,2-diol was employed.

<sup>d</sup>A mixture of *cis*- and *trans*-1,2-diols was employed.

<sup>e</sup>Methyl acrylate (400 mol%).

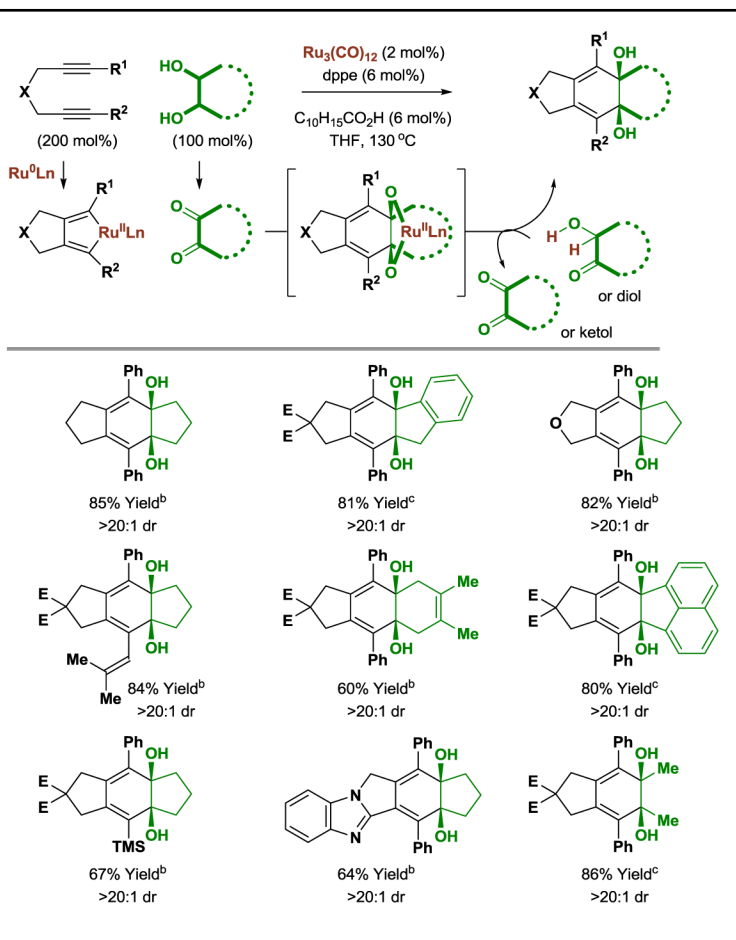
Table 3

Ruthenium(0) catalyzed [4+2] cycloaddition of *ortho*-acetylenic benzaldehydes with  $\alpha$ -ketols.<sup>a</sup>

<sup>a</sup>Yields are of material isolated by silica gel chromatography. CyJohnPhos = 2-(dicyclohexylphosphino)biphenyl. RuPhos = 2-dicyclohexylphosphino-2',6'-diisopropoxybiphenyl.

<sup>b</sup> $\text{Ru}_3(\text{CO})_{12}$  (3 mol%), RuPhos (18 mol%).

Table 4

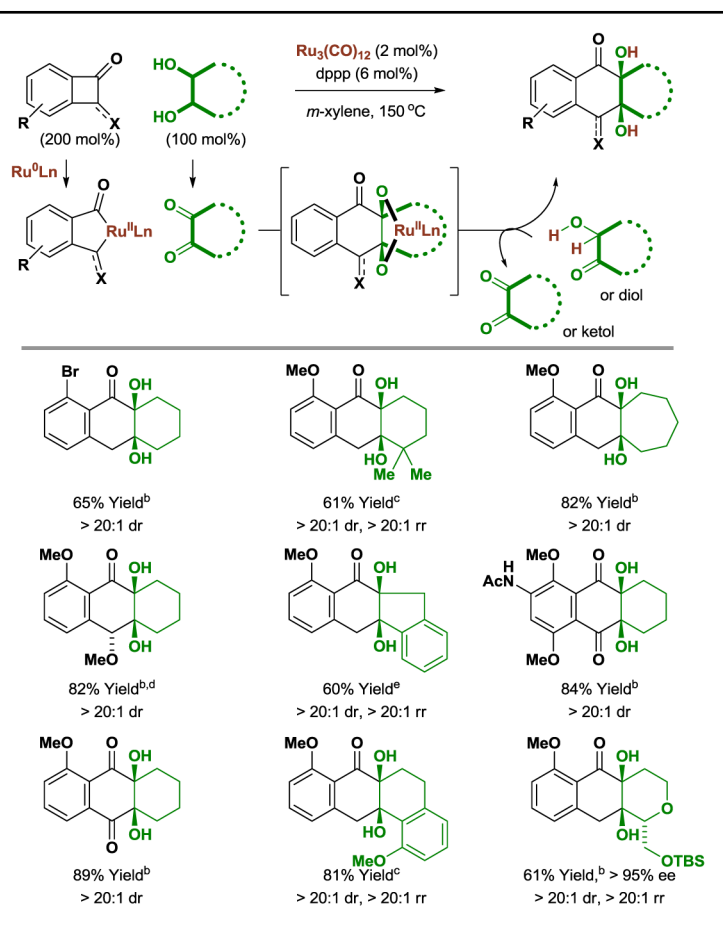
Ruthenium(0) catalyzed [2+2+2] cycloaddition of diols with 1,6-diynes.<sup>a</sup>

<sup>a</sup>Yields are of material isolated by silica gel chromatography. dppe = *bis*-(diphenylphosphino)ethane.  $\text{C}_{10}\text{H}_{15}\text{CO}_2\text{H}$  refers to 1-adamantanecarboxylic acid. E =  $\text{CO}_2\text{Et}$ .

<sup>b</sup>The *cis*-1,2-diol was employed.

<sup>c</sup>A mixture of *cis*- and *trans*-1,2-diols was employed.

Table 5

Ruthenium(0) catalyzed [4+2] cycloaddition of diols with benzocyclobutenones.<sup>a</sup><sup>a</sup>Yields are of material isolated by silica gel chromatography. dppp = *bis*-(diphenylphosphino)propane.<sup>b</sup>The *trans*-1,2-diol was employed.<sup>c</sup>Reaction conducted from the ketol oxidation level.<sup>d</sup>130 °C.<sup>e</sup>A mixture of *cis*- and *trans*-1,2-diols was employed.